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Research and Development

MISCIBILITY, SOLUBILITY, VISCOSITY, AND DENSITY MEASUREMENTS FOR R-236fa WITH POTENTIAL LUBRICANTS

Prepared for

Strategic Environmental Research
and Development Program

Prepared by

National Risk Management
Research Laboratory
Research Triangle Park, NC 27711

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MISCIBILITY, SOLUBILITY, VISCOSITY, AND DENSITY MEASUREMENTS FOR R-236fa WITH POTENTIAL LUBRICANTS

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ABSTRACT

Miscibility, solubility, viscosity, and density data are needed to determine the suitability of refrigerant/lubricant combinations for use in refrigeration systems. These property data have been obtained for HFC (hydrofluorocarbon) -236fa and two potential lubricants. The tested oils were a ISO68 pentaerythritol ester mixed-acid, hereafter referred to as Castrol SW-68 manufactured by Castrol, and a ISO46 polyol ester mixed-acid, hereafter referred to as Mobil Arctic-46 manufactured by Mobil.

The miscibility tests were performed in a test facility consisting of a series of miniature test cells submerged in a constant temperature bath. The bath temperature was precisely controlled over a temperature range of -50 to 90°C (-58 to 194°F). The test cells were constructed to allow for complete visibility of the refrigerant/lubricant mixtures under all test conditions. Critical solution temperatures obtained from the miscibility data are presented for each refrigerant/lubricant combination. The oils tested, namely Castrol SW-68 and Mobil Arctic-46, were found to be completely miscible over the temperature and concentration ranges tested.

Solubility, viscosity, and density data were also obtained for R-236fa mixed with the two oils for a refrigerant concentration range of 0 to 40 weight percentage refrigerant over a temperature range of 30 to 100°C (86 to 212°F). This range of conditions represents the area of interest necessary for the proper design of compressors. This research shows that the solubility, viscosity, and density are functions of temperature and concentration. This research also shows that (1) the solubility increases with increasing temperature and with increasing refrigerant concentration (i.e., mass fraction of refrigerant), (2) the viscosity decreases with increasing temperature and with increasing refrigerant concentration, and (3) the density decreases with increasing temperature but increases with increasing refrigerant concentration. In addition to presenting the above test results, the R-236fa with Castrol SW-68 data in this study were also compared to R-236ea and R-114 mixed with the Castrol SW-68 and naphthenic mineral oil, respectively.

This report was submitted in fulfillment of Purchase Order No. 5D2687 NAEX by Iowa State University under the sponsorship of the U.S. Environmental Protection Agency with funding from the Department of Defense's Strategic Environmental Research and Development Program*. This report covers a period from March 1996 to March 1997.

* A joint program of the Department of Defense, the Department of Energy, and the Environmental Protection Agency.

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CHAPTER 1

INTRODUCTION

1-1. MISCIBILITY OF R-236fa AND LUBRICANT MIXTURES

The development of acceptable refrigerants requires the identification of compatible lubricants so that refrigeration systems with mechanical compressors will operate properly. The first requirement of a compatible lubricant is that it be miscible with the refrigerant over the operating temperatures of the system. Refrigeration systems require a miscible refrigerant/lubricant mixture for compressor lubrication, for maximum heat transfer performance in the evaporator, and for proper lubricant return to the compressor.

To obtain miscibility data, the visual observation and careful interpretation of the physical conditions of a refrigerant/lubricant mixture at specific temperatures are necessary. The procedure is repeated for the desired ranges of temperatures and refrigerant concentrations. Visual inspection of the mixture allows for determination of whether the mixture showed signs of cloudiness, floc or precipitate formation, and/or the formation of a second liquid phase.

Miscibility data were measured for HFC (hydrofluorocarbon)-236fa, hereafter designated as R-236fa, mixed with two different polyol ester (POE) lubricants which represent typical commercially available POE lubricants of the pentaerythritol mixed-acid type, hereafter designated as Castrol SW-68 and Mobil Arctic-46.

Miscibility tests were performed on R-236fa/lubricant mixtures for refrigerant concentrations of 25 to 85% by weight. These tests were performed by keeping the refrigerant/lubricant mixture visible at all times, while controlling temperatures to ±1°C (±1.8°F) and shaking the test cells to mix the contents. Each refrigerant/lubricant combination was tested for miscibility in 10°C (18°F) increments over the test temperature range of -40 to +90°C (-40 to +194°F).

1-2. SOLUBILITY, VISCOSITY, AND DENSITY OF REFRIGERANT/LUBRICANT MIXTURES

When introducing a new refrigerant, the choice of lubricant is important in that the role of the lubricant in the refrigeration system is to lubricate the compressor. The acceptability of many alternative refrigerants (i.e., HFCs) and their respective lubricants has been designed around duplicating the solubility and viscosity characteristics of the present CFCs (chlorofluorocarbons)/HCFCs (hydrochlorofluorocarbons) and mineral oil

mixtures. The degree of solubility and viscosity required has become a point of discussion in the R & HVAC (refrigerating and heating, ventilating, and air conditioning) industry.

Having decided on the lubricant to be used, the design engineer needs refrigerant and lubricant mixture data in order to properly design the refrigeration system. For example, a design engineer needs to know what the pressure and temperature relationship is for the refrigerant and lubricant mixture as the concentration of each component changes. The above relationship between pressure, temperature, and concentration is known as solubility. Viscosity data are needed because the viscosity of a refrigerant/lubricant mixture changes as refrigerant is added to the mixture. The solubility and viscosity data needed for design using a R-114 replacement such as R-236fa were unknown before this work was conducted.

The main types of lubricants recently being proposed for use with the new refrigerants are PAGs (poly alkyl glycols), modified PAGs, and POEs. This research presents property data consisting of solubility, viscosity, and density data for R-236fa with two different lubricants. As noted earlier, these lubricants represent typical commercially available POE lubricants of the pentaerythritol mixed-acid type and are designated as Castrol SW-68 and Mobil Arctic-46.

The objectives of this research were to obtain data for R-236fa with two different lubricants. These data will be useful for designing compressors for a non-CFC refrigerant which is presently used with R-114 aboard U.S. Navy ships. The solubility, viscosity, and density data were obtained for the following conditions:

- Composition: 0 to 40 weight percent refrigerant
- Temperature: 30 to 100 °C (86 to 212 °F)
- Pressure: 0 to 3.5 MPa (0 to 500 psia)

The following chapters describe the test facility and the methodology used to measure the properties of miscibility, solubility, viscosity, and density. The property results for the refrigerant/lubricant pairs studied were presented in the form of graphs and empirical correlations. The data were also tabulated.

CHAPTER 2

CONCLUSIONS

2-1. MISCIBILITY OF R-236fa AND LUBRICANT MIXTURES

Critically needed miscibility data have been obtained for R-236fa with two polyol ester (POE) lubricants. The test facility incorporates test cells with sight windows for viewing the refrigerant/lubricant mixture inside. The cells were charged with variable amounts of refrigerant and lubricant to facilitate refrigerant compositions from 0 to 100% by refrigerant mass fraction. After charging, the test cells were submerged in either the low temperature or high temperature baths which could be set to any described temperature. Operating temperature and pressure ranges for the facility are -50 to 90°C (-58 to 194°F) and 0 to 3.5 MPa (0 to 500 psia), respectively.

Data for the R-236fa in each of the test lubricants have been collected for refrigerant concentrations of 25 to 85%. The raw data have been presented and the results have been summarized. The two test lubricants, namely Castrol SW-68 and Mobil Arctic-46, were found to be completely miscible over the temperature and concentration ranges tested.

2-2. SOLUBILITY, VISCOSITY, AND DENSITY OF REFRIGERANT/LUBRICANT MIXTURES

In this study, a test facility developed by Van Gaalen, et al. (1991a,b) was used to provide critically needed refrigerant/lubricant mixture properties. Specifically, solubility, viscosity, and density data were obtained and correlated as functions of temperature, pressure, and refrigerant concentration over various ranges of pressures and temperatures for two different lubricants mixed with R-236fa. Data were obtained using the test facility with the operating temperature and pressure ranges of 30 to 100°C (86 to 212°F) and 0 to 3.5 MPa (0 to 500 psia), respectively.

Experimental procedures for the operation of the test facility are described here. Also, the data reduction techniques, including correlating equations, are presented. The measured data showed that the instrumentation was accurate and the results were repeatable. The test facility has been successfully employed to obtain experimental

results for refrigerant/lubricant mixtures of R-236fa in two different lubricants: Castrol SW-68 and Mobil Arctic-46.

This research shows that the solubility, viscosity, and density are functions of temperature and concentration. Specifically, (1) the solubility increases with increasing temperature and with increasing refrigerant concentration (i.e., mass fraction of refrigerant), (2) the viscosity decreases with increasing temperature and with increasing refrigerant concentration, and (3) the density decreases with increasing temperature but increases with increasing refrigerant concentration.

The results are also presented in charts where the solubility, dynamic viscosity, kinematic viscosity, and density are plotted as functions of temperature and refrigerant concentration. Empirical correlating equations were developed using multilinear regression analysis. These equations allow convenient interpolation of the data at specific property conditions.

2-3. COMPARISON OF R-236fa, R-236ea, AND R-114 WITH LUBRICANTS

In addition to presenting the above test results, the R-236fa with Castrol SW-68 data in this study were also compared to R-236fa with Mobil Arctic-46, R-236ea and R-114 mixed with the Castrol SW-68 and naphthenic mineral oil, respectively.

The results of the R-236ea and Castrol SW-68 along with the results of the R-114 and naphthenic mineral oil were reported in a study by Zoz and Pate(1996). The results of this comparison are presented in both charts and tables for miscibility, solubility, dynamic viscosity, kinematic viscosity, and density at various temperatures and refrigerant concentrations. The miscibility tests showed that R-236fa/Arctic-46, R-236fa/SW-68, R-236ea/SW-68, and R-114/naphthenic mineral oil were all miscible over the -40 to 90°C (-40 to 194°F) temperature range of the test.

The results of the solubility, viscosity, and density tests for R-236fa mixed with Castrol SW-68 were similar to the results for R-236fa mixed with Mobil Arctic-46, R-236ea mixed with Castrol SW-68, and R-114 mixed with naphthenic mineral oil which indicates that it can be a suitable replacement for R-114 mixed with a mineral oil.

CHAPTER 3

LUBRICANT/REFRIGERANT TEST FACILITY

3-1. MISCIBILITY TEST FACILITY

The test facility for measuring miscibility includes test cells capable of withstanding the high pressures and the extreme temperatures encountered in the study of refrigerant/lubricant mixtures. Two constant temperature baths maintain the temperature of the test cell constant. The facility was designed for the purpose of determining the miscibility characteristics of refrigerant/lubricant mixtures over the temperature range of -40 to 90°C (-40 to 194°F) and for pressures up to 3.5 MPa (500 psia). The test cells have glass viewports and are submerged in one of two constant temperature baths so that the miscibility characteristics of the mixture can be observed and recorded. The test facility is described in detail in previous publications (Zoz, 1994 and Zoz and Pate, 1993). Figure 3.1 is a photograph of miscibility test facility.

The precise fluid temperature of each bath was measured by a platinum resistance temperature detector (RTD) that was connected to a signal conditioner/current transmitter. The RTD had an accuracy of $\pm$0.1°C ($\pm$0.18°F). Since the miscibility characteristics of mixtures in each cell were noted at 10°C (18°F) intervals in this study, the uncertainty in the temperature where a change in the miscibility characteristics occurred was ±5°C (±9°F). Due to the magnitude of this uncertainty, the uncertainty in the actual temperature measurements using the RTD was insignificant.

3-1-1. TEST CELLS

The test cells are constructed to allow for complete visibility of the lubricant/refrigerant mixture at all test conditions. Each test cell consists of a double-port, seal-cap type liquid indicator, which is essentially a 3.17-cm (1.25-in.) pipe cross with sight windows screwed into opposing ports. Valves for charging the refrigerant into the cell are screwed into the other two ports. A temperature sensor can be inserted in each cell or in an adjoining reference cell exposed to the same heating or cooling conditions.

The overall volume of each test cell was measured to be 65-ml (3.963-in^3). During charging. each cell can be filled so that the vapor space is less than 15% of the total volume. In addition. if temperature and pressure data are available. changes in the liquid concentration due to the vapor space refrigerant can be calculated.

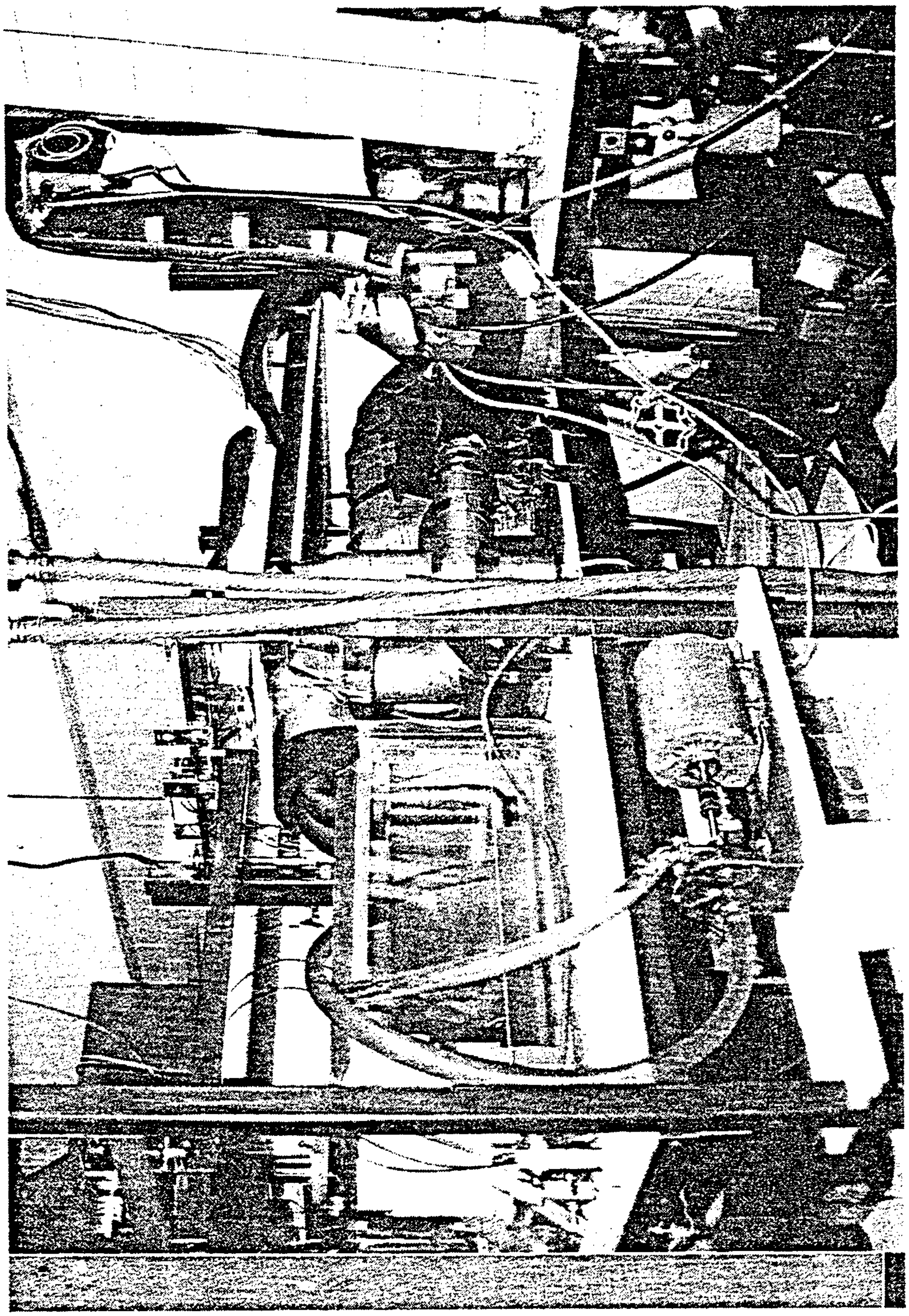

Figure 3.1. Photograph of the miscibility test facility

Three charged cells can be placed in a specially designed Plexiglas™ holder, and two such holders can be placed in the constant temperature bath to permit the testing of six test cells simultaneously.

3-1-2. CONSTANT TEMPERATURE BATHS

The temperature of the cells is fixed by placing them in one of two constant temperature baths. The hot bath is used to maintain temperatures from 10 to 95°C (50 to 203°F), while the cold bath is used for temperatures in the range of 10 to -50°C (50 to -58°F).

The baths are constructed of glass which allows complete visibility of the test cell and, therefore, the lubricant/refrigerant mixture can be observed through the glass. Movable fluorescent lights are located behind a bath to help increase visibility.

3-1-2-1. COLD BATH

The cold bath fluid is composed of 65% pure ethylene glycol and 35% water which prevents the bath fluid from freezing while still allowing the bath fluid to be transparent. The bath is cooled with the use of an R-502 refrigeration system. A temperature controller and a heater are installed to regulate the bath temperature.

The bath is insulated on all sides to ensure a uniform temperature. The insulation on the front and back of the bath consists of a double-paned Plexiglas™ window mounted on the glass bath. Condensation is prevented by using a nitrogen purge of the dead air spaces. Insulation on the other sides is provided by 0.0508 m (2 in.) of Styrofoam™.

3-1-2-2. HOT BATH

The hot bath fluid is water with a rust inhibitor added. 0.0508 m (2 in.) of Styrofoam™ provides the insulation on the ends of the bath, while the insulation on the front and back of the bath is provided by a single Plexiglas™ window mounted on the glass so as to leave a 0.0127 m (1/2-in.) air space.

3-1-3. INSTRUMENTATION

The precise temperature of the bath fluid is measured by two internal resistance temperature detectors (RTDs). These primary temperature probes consist of a platinum RTD connected to a signal conditioner/current transmitter that provides a linear response over the temperature range of -51 to 149°C (-60 to 300°F). The RTD's

have an accuracy of ±0.1°C. A microcomputer and data acquisition hardware under the direction of a data acquisition program receive and record signals from all instruments.

One cell in each bath is assembled with an internal RTD to determine equilibrium conditions and hence steady-state conditions. This particular cell is charged with pure lubricant to provide a "worst case" heat transfer situation. The temperature difference between the internal RTD and the bath temperature indicates when thermal equilibrium between the cell and the bath has been achieved. Steady-state conditions are typically achieved about 30 minutes after a change of about 5 to 10°C in the circulating bath temperature is made.

3-1-4. EXPERIMENTAL PROCEDURE

Experimental procedures have been developed for measuring refrigerant/lubricant miscibility by using the test facility described previously. The cells are first cleaned with the front and back windows removed for cleaning. After cleaning, the back window is installed and tightened. The prescribed amount of lubricant is injected with a syringe through the front window space. The front window is then replaced and tightened. A vacuum pump is hooked up to a port housing one of the valves, and a vacuum is pulled to remove any dissolved moisture or air. Fittings are retightened if a failure to hold either a vacuum or a set pressure indicates that this is necessary.

Liquid refrigerant is injected into the cell from the refrigerant canister by using a manifold that allows for the evacuation of the connecting lines. The cells are weighed on a scale before and after the injection of the lubricant and the refrigerant. The typical weight of cells is approximately 1459.5 grams. The scale has an uncertainty of ±0.01gram. The concentration of the liquid in each cell is calculated from the masses of refrigerant and lubricant injected. The uncertainty in the concentration measurements is ±0.5%. It is important to note that since the refrigerant vapor density changes as the temperature and pressure change, then the refrigerant vapor mass also varies. As a result, the liquid concentration varies slightly as the temperature and pressure change. For the experimental approach presented here, the vapor volumes are kept small. Less than 10% of the total space is vapor. Therefore, the overall variations in refrigerant concentration as the temperature and pressure are changed during any particular test are minimized. Once the desired amounts of lubricant and refrigerant have been injected into the cell, it is ready for testing.

The cells are then placed in the bath and heated or cooled to the desired temperature. The desired temperatures are in 10°C increments for heating from 10 to 90°C or for cooling from 10 to -50°C. Steady-state conditions are achieved when two conditions are met: firstly, the bath temperature is within ±0.5°C of the set point temperature which can be obtained by using the two RTDs in the bath with signal conditioner/current transmitter and secondly, the difference between the instrumented cell and the bath temperature is within 0.5°C which also can be obtained by using two RTD's in the bath with a internal RTD in one particular cell which was mentioned earlier. The next step is to record the characteristics of the fluid in each cell.

After testing and removing the cells from the bath, the refrigerant/lubricant mixture is drained through one of the valves, and the cell is rinsed three times with solvent. The final cleaning of the cell is accomplished by removing the front and back windows and rinsing the cell with solvent to remove traces of lubricant. The windows and seals are then cleaned and visually examined for defects.

3-1-5. MISCIBILITY CHARACTERISTICS

When a refrigerant/lubricant mixture is miscible, it appears as a homogeneous transparent solution. However, when a refrigerant/lubricant mixture is immiscible, there is either cloudiness, evidence of particles dispersed throughout the mixture, or there are two liquid phases present in the cell. Throughout all testing, visual inspections were made for any of these signs of immiscibility.

3-1-6. REFRIGERANT CONCENTRATION

The refrigerant concentration of each test cell was calculated from the total masses of refrigerant and lubricant charged into the cell. The uncertainty in the concentration measurements depends on the concentration that is being considered, however, the maximum uncertainty in concentration is ± 0.005 (0.5%). The uncertainty was calculated by using a propagation-of-error method discussed by Beckwith et al. (1982).

It is important to note that the concentration of the liquid phase in the test cell changed as the temperature of the cell was varied. This occurred because a vapor space was required above the liquid mixture to accommodate the thermal expansion of the liquid mixture. If it were not for this vapor space cell, failure could occur due to extremely high pressures internal to the cell. Changes in concentrations due to the vapor space were less than 1% over the full range of temperatures tested.

3-1-7. CRITICAL SOLUTION TEMPERATURES

The critical solution temperature, as defined in the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) Refrigeration Handbook (1994), is the temperature above which a refrigerant/lubricant combination is miscible for all refrigerant concentrations. Since some of the new refrigerant/lubricant combinations have regions of immiscibility that occur with increasing temperature (sometimes referred to as a high temperature immiscibility), an additional definition must be used. The lower critical solution temperatures presented here are based on the ASHRAE definition, while the upper critical solution temperature is defined as the temperature below which a refrigerant/lubricant combination is miscible for all refrigerant concentrations.

3-2. SUMMARY OF MISCIBILITY TEST FACILITY

A versatile lubricant/refrigerant miscibility test facility has been described to provide critically needed miscibility data for a variety of lubricant/refrigerant mixtures over a range of temperatures and concentrations. Incorporating commercially available test cells. as well as windows for observation of the test cells contents, the test facility can be used for determination of the miscibility of these mixtures. Precise, convenient charging of mixtures with refrigerant compositions ranging from 10 to 90% by weight is possible. These tests were performed by keeping the refrigerant/lubricant mixture visible at all times, by controlling temperatures to ±1°C (±1.8°F), and by shaking the test cells to mix the contents. Each refrigerant/lubricant combination was tested for miscibility in 10°C (18°F) increments over the test temperature range of -40 to +90°C (-40 to +194°F).

3-3. SOLUBILITY, VISCOSITY, AND DENSITY TEST FACILITY

The method used in this study to measure the properties of solubility, viscosity, and density for refrigerant/lubricant mixtures was described in detail by Van Gaalen, et al. (1991a,b). The apparatus consists of a pressure vessel (hereafter referred to as the test cell) charged with known refrigerant/lubricant mixtures and a support system capable of controlling the temperature of the test cell. The test cell, support system, and data acquisition system were designed to measure solubility, viscosity, and density for any lubricant/refrigerant mixture over a normal operating temperature range of 30 to 100°C (86 to 212°F) and for pressures up to 3.5 MPa (500 psia).

The test facility, including instrumentation, data acquisition, and procedure for injecting fluids into the test cell are described in the following sections. The test facility, including the test cell, its major components, and instrumentation, and methods of injecting fluids, was described previously by Van Gaalen, et al. (1991a,b).

3-3-1. TEST CELL

The test cell is a cylinder constructed of Schedule 120 Type 304 stainless steel pipe, with an outside diameter of 141.3-mm (5.563-in.), a wall thickness of 12.7-mm (0.5-in.), and a corresponding inside diameter of 115.9-mm (4.563-in.). The length of the pipe was 457.5-mm (18-in.). The test cell stands upright on one end. Two diametrically opposite slots, 317.5-mm (12.5-in.) in width, were machined through the cylinder wall. Windows bolted into position over these slots allowed visual inspection of the contents at all times and under all test conditions. A schematic drawing of the test cell is provided in Figure 3.2.

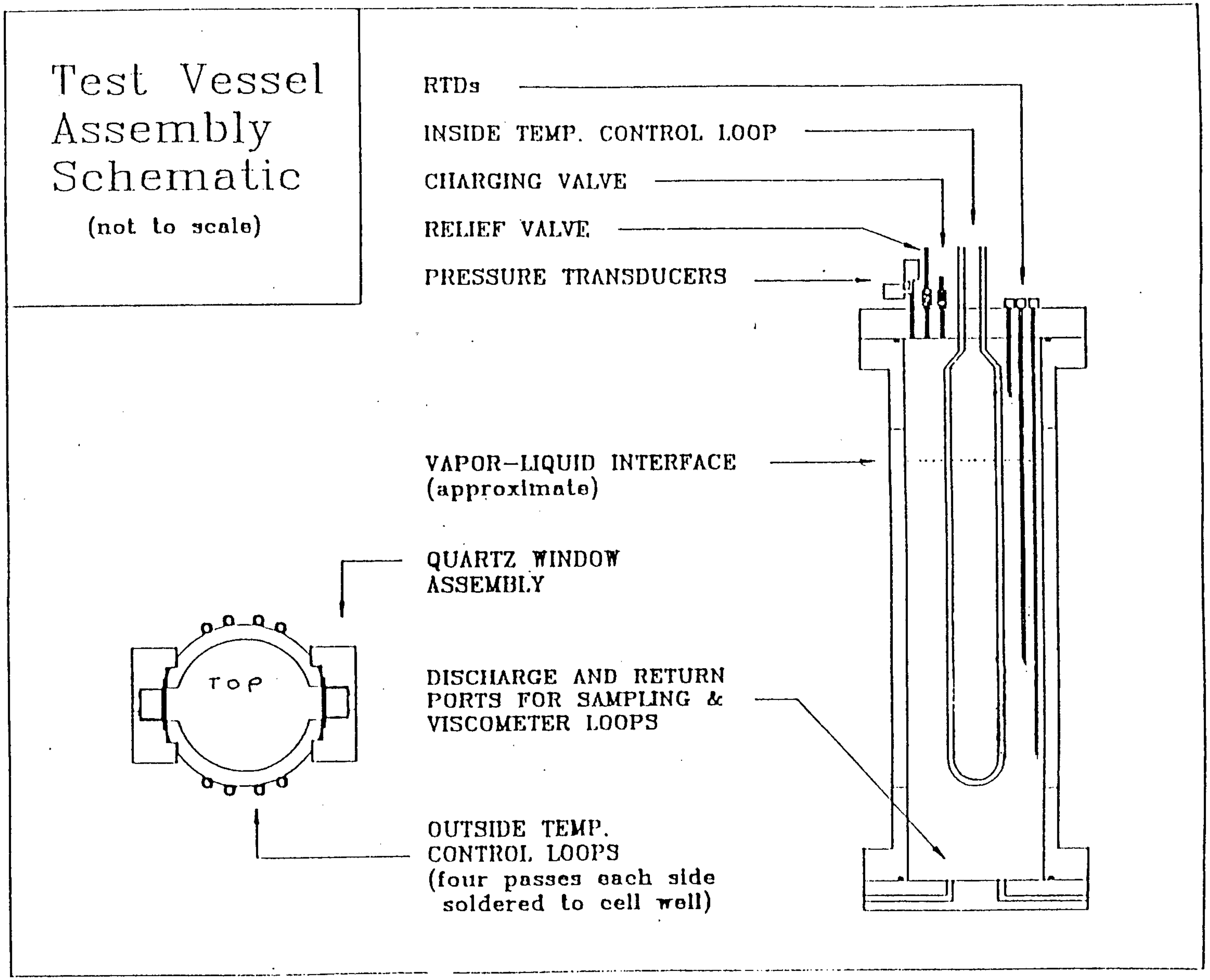

Figure 3.2. Schematic drawing of the test cell

Machined end plates 25.4-mm (1-in.) thick were bolted onto flanges welded to the pipe section at each end. An O-ring at each end, seated in machined grooves in the wall of the pipe section, provided the pressure (and vacuum) seals. Because none of the welded joints were exposed to the contents of the test cell, this method of construction obviated the need for inspection of welds for leakage that would be required by other designs. The height of the test cell is sufficient to accommodate the addition of 40 % (by mass) refrigerant to the liquid oil charge, while still reserving a minimum vapor space at all expected densities and at maximum charge conditions.

Entering the test cell through the top end plate are three temperature probes and a heating/cooling coil, as depicted in Figure 3.2. Also provided in the top plate are ports for pressure measurement and pressure relief, as well as for filling and evacuation of the test cell. Two ports machined into the bottom plate allowed for the exit and return of fluid to/from the external viscometer and sampling loops, as shown in Figure 3.2. The actual volume of the test cell and associated loops was determined and scales on the windows calibrated by injecting precise amounts of solvent from the charging system, which had been previously calibrated. With both windows mounted on the test cell and with the viscometer and sample loops full, the overall volume was measured as 5190-mL $\pm$ 20-mL (317-in^3 $\pm$ 1.22-in^3). Liquid and vapor volume were correlated with liquid level height as measured on the scales.

The temperature, and hence pressure, of the solution under test is controlled by a temperature control flow loop having coils soldered on the exterior of the test cell and by a portion of the loop immersed in the test cell. A heating fluid is supplied to this loop by a circulating bath. Uniform heating of a large surface area minimizes the thermal gradients in the oil/refrigerant mixture. Fiberglass insulation, 50-mm (2-in.) thick around the test cell, minimizes heat loss to the environment. A walled enclosure, described elsewhere, also reduces heat losses.

3-3-2. WINDOWS

Two diametrically opposite vertical windows were provided in the test cell wall for the purpose of viewing the contents of the test cell. Viewing is necessary for detecting the presence of more than one phase and for density determinations, as well as for aiding the charging of the test cell. The viewing slots are 304.8-mm (12-in.) long and 12.7-mm (0.50-in.) wide. Calibrated scales fastened to the retainer plates adjacent to the viewing slots enable measurement of the height of the liquid-vapor interface to within $\pm$ 0.8-mm ($\pm$ 0.03-in.). This permits determination of the volumes of liquid and vapor present to within $\pm$ 9-mL ($\pm$0.55-in^3), or less than 0.2 % of the total cell volume. Quartz pieces set on O-rings and held in place by retainer plates provide the pressure seal. A stainless steel backing plate holds the quartz against the O-ring in the slot. The whole assembly is then bolted onto the test cell and sealed by another (larger) O-ring compressed between the test cell wall and the window assembly. The O-ring material must be compatible with the lubricant/refrigerant mixtures to which it will be exposed. Neoprene O-rings were used with the R-236ea/lubricant mixtures. Viton O-rings have also proven satisfactory in

later work with the same combination of refrigerant/lubricant mixtures. After installation, a hydrostatic test to 3.5 MPa (500 psia) conducted at ambient temperature proved that the windows were leak-tight. Additional pressure tests with nitrogen gas at 3.5 MPa (500 psia) also showed no leaks.

3-3-3. TEMPERATURE CONTROL FLOW LOOP

A flow loop for controlling the temperature of the test cell is installed. Figure 3.3 shows a schematic diagram of this loop. The loop has two coils of 9.525-mm (0.375-in.) OD Type 304 stainless steel tubing in parallel, one soldered in place around the test cell wall and the other immersed in the test cell through the top plate. The exterior portion of this loop is further divided into two parts, with each part heating one side of the test cell. The interior portion also bifurcates to provide more thermal contact area. The routing of these internal loop portions was arranged so that they did not obstruct the view through the windows.

A circulating bath maintains the desired temperature of the heating fluid by controlling a 3.0 kW heating element. The heating fluid is a poly-alpha-olefin (PAO), which has a useful range from -30 to 380°C (-22 to 716° F). While the viscosity of PAO at the lower end of this temperature range, -30°C (-22F), is high for achieving turbulent flow in the loop with the circulating bath pump, it performs well at higher temperatures in an open system because of its decreasing viscosity and low volatility. The steady-state temperature of the contents of the test cell is indirectly controlled by setting the temperature of the heating fluid in the flow loop. Operating experience has shown that adequate heating of the test cell is provided by this arrangement. Steady-state conditions are typically achieved from 2 to 3 hours after a 10°C (18°F) change in the circulating bath temperature set point. The temperature of the liquid phase of the refrigerant and lubricant mixture inside of the cell is measured by the three internal resistance temperature detectors (RTDs). However, these three RTD's show that the cell contents are at a uniform temperature especially since the liquid phase is well stirred. An average of these liquid temperatures in the cell is used in the reporting of the liquid density data.

3-3-4. VISCOMETER

Two commercially available viscosity sensors were installed in the auxiliary viscosity loop. The sensors were Cambridge Applied Systems (CAS 1989) model ND300 with piston style viscosity-temperature sensor. The viscosity sensor operation is based on a movable piston drawn through the fluid in the internal cavity by an applied electromagnetic field. The time elapsed as the piston travels through a known distance is a measure of the viscosity of the fluid. The associated circuit card provides electronics for control and sensing, giving a 0-to 2-volt D.C.

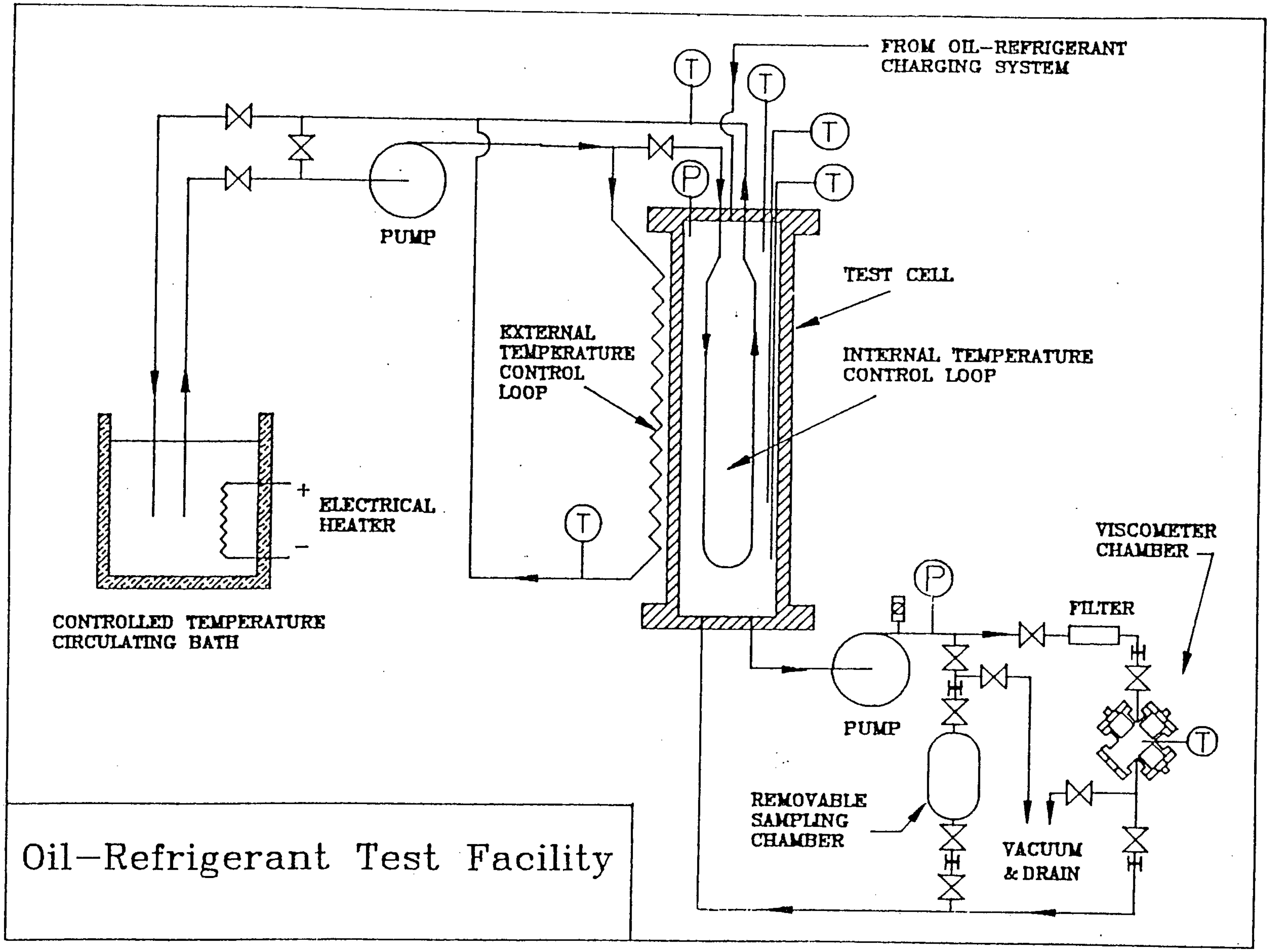

Figure 3.3. Schematic diagram of the flow loop

signal correlated to viscosity. The uncertainty of the viscosity data is ±2.0% of the reading. Each sensor also contains an RTD for measurement of the local temperature, which is used in the reporting of the viscosity data. Because of internal self-heating in the viscometer that arises from the dissipation of electrical energy in the drive coils of the sensor, this RTD reading is somewhat higher than the temperatures indicated by the RTDs in the test cell during steady-state operation. This is especially true at the lower end of the investigated temperature range. For example, at 40°C the difference is about 3 to 4°C, depending on the particular viscosity sensor. This difference decreases to about zero at temperatures of 90°C and above.

The two viscosity sensors that are installed in the viscometer chamber have viscosity ranges of 1 to 20 cP (centipoise), and 10 to 200 cP, respectively. Because these ranges overlap, some limited redundant measurements of viscosity are possible, thus increasing the confidence in the validity of the calibrations of each sensor. The viscosity sensors were calibrated by using standard viscosity fluids provided by the Cannon Instrument Company. Use of multiple sensors reduces the downtime that would otherwise be required to change the internal piston of a single sensor to the desired measurement range. Note that pistons are available from the manufacturer for viscosities up to 5000 cP, should they be necessary for measurements at low temperatures where the lubricant/refrigerant solutions may be very viscous.

Internal self-heating in the drive coils of the viscometer tends to cause vapor to flash from the equilibrium mixture. This vapor formation was disruptive to stable and accurate operation of the viscometer in early testing. For this reason, it was necessary to construct an external flow loop through which the liquid mixture was compressed before being pumped to the viscometer for measurement and then returned to the test cell. In this manner, stable and repeatable viscosity readings were achieved. Taking liquid from the test cell, a pump in the loop raises the pressure of the liquid without noticeably affecting the temperature. Since a small increase in pressure has a negligible effect on liquid viscosity, this pressurization provides an acceptable means of preventing vapor formation in the viscometer.

Figure 3.4 shows a schematic diagram of the viscosity-temperature sensor body. As shown in Figure 3.4, a magnetically driven positive displacement gear pump with a variable speed motor moves the fluid through this loop to the viscometer chamber and back to the test cell. Variable speed control allows for adjustment of flow from almost zero to about 0.095 L/s (1.5 gpm), which provides for sufficient pressurization of the liquid in the loop while limiting uncontrolled heating of the fluid due to the addition of pumping power. A valve between the viscometer chamber and the discharge to the test cell can be adjusted, along with the flow rate, to produce the required pump discharge pressure at a reasonable flow rate. A pressure gauge is installed at the pump discharge to monitor the pressure increase. A pressure relief valve set to open at 3.5MPa (500psia) is installed just downstream

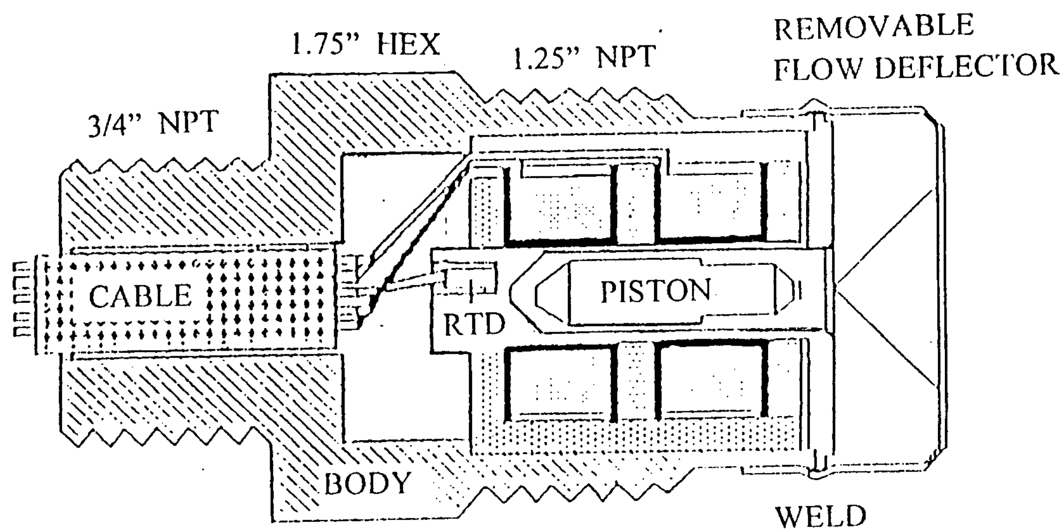

Figure 3.4 Viscosity-Temperature sensor body

of the pump discharge to provide a safe release of fluid if the downstream flow is inadvertently blocked by the closing of a valve or other restriction.

The chamber that holds the viscometer is constructed from a 31.75-mm NPT (1.25-in.) stainless steel pipe cross. Each of the viscosity sensors threads into a branch of the pipe cross. The fourth branch is plugged for possible future use. Passing over an in-line thermocouple, which provides a rough check of the temperature, fluid enters the chamber through a fitting in the side of the pipe cross. The fluid then flows around the active portion of the viscosity sensors before returning to the test cell through the 6.35-mm (0.25-in.) diameter return line.

The inlet and outlet lines contain valves to isolate the chamber for removal or disassembly. A vacuum/drain port is connected to the return line to allow removal of fluid after isolation of the chamber from the test cell before disassembly and to enable the necessary evacuation of the chamber after reinstallation into the loop. The total volume of the liquid contained in this loop is 57.5 mL (3.51 in^3.), which is 1.2% of the total system volume.

3-3-5. SAMPLING LOOP

A 75-mL (4.6-in^3) sampling cylinder is connected in parallel with the viscometer and may be independently isolated and removed from the system for measurements of the liquid composition. The sampling loop was assembled with this cylinder and two union bonnet valves on each side. The outer valves may be closed to isolate the chamber from the rest of the system, and the inner valves are closed to ensure that no fluid escapes from the sampling cylinder when it is removed. A vacuum/drain port is also provided. The total volume of the sampling loop is 79 mL (4.8-in^3). Since this is 1.6% of the total system volume, disturbances of test cell conditions are minimized during sampling.

3-3-6. EQUIPMENT ENCLOSURE

Although all components of the facility are insulated, a frame and panel enclosure consisting primarily of steel framing, plywood, fiberglass ductboard, and Plexiglas™ viewports was constructed to provide additional isolation from the room environment. This provides greater thermal uniformity and stability as well as affording a measure of protection to operators in the event of a high-pressure leak of the hot lubricant/refrigerant mixture. At the same time, the enclosure was designed to allow accessibility and visibility for proper operation and monitoring.

3-3-7. DATA ACQUISITION

Viscosities, temperatures, and pressures are recorded by computerized data acquisition methods. A microcomputer controls a digital multimeter and a switching unit which provides a sufficient number of channels to monitor all signals generated by the installed sensors. Table 3.1 summarizes sensor ranges and precisions.

A bonded strain gauge pressure transducer is in contact with the test cell contents via a port machined into the top plate. A second pressure transducer employs a capacitance-sensing element. The calibrations of these pressure transducers were checked with the use of a dead-weight pressure tester. These calibration checks indicated that the output signals of both transducers were linear with pressure, matching the factory-supplied calibrations. The uncertainty in the pressure data is ± 5.1 kPa (± 0.75 psia).

Three platinum RTDs independently track the temperature of the liquid contained in the test cell, and another RTD monitors the vapor space temperature. A fifth RTD is inserted into the pipe cross containing the viscometers. Three RTDs were calibrated after connection with current transmitters, the required load resistors, and a power supply.

Table 3.1. Summary of the range and precision of the sensors

Instrument	Range	Precision
Bonded Strain Pressure Transducer	0 - 3.5 MPa (0 - 500 psia)	± 5.1 kPa (± 0.75 psia)
Variable Capacitance Pressure transducer	0 - 3.5 MPa (0 - 500 psia)	± 3.8 kPa (± 0.55 psia)
Viscometer	1.0 - 200 cP	± 2 % rdg.
Platinum RTD and Signal Conditioner	-50°C - 150°C (-58°F - 302°F)	± 0.1°C (± 0.2°F)
Concentration measurements	0 - 100 %	± 1 %

The signal conditioners used with the RTDs linealize the response, providing a 4-to 20-mA signal that is linear over the temperature range of -50 to 150°C (- 58 to 302°F). This signal produces a 1-to 5-volt output when measured across a 250-ohm load resistor, which is monitored by the data acquisition equipment. The calibration of output voltage versus. temperature showed that all RTDs provided a linear response. The uncertainty of these temperature measurements was ±0.2°F (0.1°C).

3-3-8. DESCRIPTION OF THE REFRIGERANT/LUBRICANT CHARGING

A charging station was designed to inject a precise amount of refrigerant into the test cell. The refrigerant is injected by a separate, parallel system. The refrigerant side employed a stainless steel cylinder of 617.8 mL (37.7 in^3) having a 50.8-mm (2-in.) bore with a 304.8-mm (12-in.) stroke. The cylinder displacements were calibrated with the use of a known solvent, and they agree with the above values to within ± 2 mL (0.1 in^3). The commercially available cylinder allowed injection of refrigerant in suitable quantities to give the desired concentration increments.

A commercial supply can is connected with the lower end of the cylinder. The cylinder is then further pressurized with nitrogen to ensure that only liquid refrigerant is contained in the cylinder. This pressure is also used to force refrigerant into the test cell.

The presence of a "slug" charge of subcooled liquid in the injection cylinder is checked by applying nitrogen pressure well above the vapor pressure of the refrigerant and ensuring no piston rod movement. The cylinder contents are then discharged to the test cell through a 9.525-mm (3/8-in.) diameter copper tube and a connecting refrigeration hose by application of pressurized nitrogen gas to the rod side of the cylinder as the charging valve on the test cell is opened. A partial injection of a given volume can be made by determining in advance the required displacement and then moving the rod to the appropriate position on a scale mounted directly behind the rod.

For the lubricant charging. the lubricant contents can be heated as a vacuum is applied in order to remove dissolved air and water vapor. The removal of air and water from the lubricant is especially important prior to injection for testing. After disconnecting the vacuum pump from the test cell. the lubricant is injected into the test cell used by the outlet valve in the lower loop which is located outside of the test cell.

3-3-9. EXPERIMENTAL PROCEDURES AND DATA REDUCTION

In addition to the description of the test facility. procedures were described for accurate and convenient measurement of the solubility. viscosity. and density of a wide range of lubricant/refrigerant solutions. This section provides a discussion of the experimental procedures that were employed to collect the data discussed in later chapters.

3-3-9-1. GENERAL EXPERIMENTAL PROCEDURES

The methods used to charge and operate the test facility vary. depending on the range of compositions and conditions desired in a particular test. A typical operating procedure for collecting viscosity. solubility. and density

data over a range of liquid-phase compositions and temperatures involves several operations. These operations. which are described in more detail later in this section, include evacuation of the test cell and auxiliary flow loops, injecting the necessary oil and refrigerant quantities. operating the gear pump to provide good mixing, heating the test cell and contents to the desired temperature. checking to ensure steady-state conditions. and taking the data. Prior to injecting another incremental charge to change the liquid concentration. cooling of the vessel contents to room temperature is required.

All measurements of pressure. temperature. and viscosity are done under programmed control of the data acquisition system described earlier. Careful recording of liquid level as the temperature changes allows the calculation of liquid density at each test condition. As explained more fully below. this also permits a calculation of the actual liquid composition, which varies slightly with temperature because of variation in the vapor and liquid densities.

3-3-9-1-1. RIG CLEANSING

Prior to the injection of any fluid for testing. the test cell and auxiliary loops are rinsed and cleaned with a sufficient amount of known solvent (which is compatible with the 0-ring material in the cell) to remove traces of any oil that had been previously tested. The 0-rings that seal the windows may also be replaced at this time if a failure to hold a vacuum or set pressure indicates that this is necessary.

3-3-9-1-2. DATA MEASUREMENT

The cell and auxiliary loops are evacuated, and the connecting hoses from the charging station are attached to a valve on the test cell. Measured amounts of refrigerant and oil are injected to provide the desired volume and concentration of liquid. The circulating pump aids the mixing of the two fluids as they are charged. It should be noted that the circulating pump is the only device used for mixing of the two fluids. The contents are then heated to desired temperatures and pressures. Then the temperatures, viscosity, and height of the liquid-vapor interface are read after checking to ensure steady-state operation. The reported pressure is the average of the pressures indicated by the two pressure transducers. The solubility pressure is reported at a liquid-vapor interface temperature taken to be the average of the temperature of the RTD in contact with vapor only and the average liquid temperature. The average liquid temperature is the mean of the temperature of the RTDs immersed in the liquid in the test cell and the RTD in the flow loop pipe cross containing the viscometers. The liquid density is reported at this temperature. The viscosity is reported at the temperature measured by an RTD inside the viscometer. which is generally slightly higher than the average liquid temperature due to the internal self-heating of the viscometer as discussed before. At each measurement point. 20 consecutive viscosity readings are recorded and the mean and standard deviation are computed. The acceptable scatter. defined as the standard deviation

divided by the mean, is taken as 1% or less. Once the limiting pressure of 3.5 MPa (500 psia) is approached, the contents are allowed to cool. More data are then collected at several steady-state test points during the cooldown phase.

3-3-9-1-3. REFRIGERANT/LUBRICANT SAMPLE EVALUATION

After the solubility and viscosity data for a given mixture have been collected over the desired temperature range, the sample cylinder is isolated and removed so that the mass fraction of refrigerant in the liquid can be determined. The procedure for determining the composition of an oil/refrigerant mixture by sampling is as follows:

- The full sample cylinder is weighed and recorded.
- One valve is slightly opened to carefully vent off the refrigerant vapor.
- The cylinder is heated to drive off the remaining refrigerant.
- The cylinder is continually weighed as the refrigerant is removed.
- Heating is continued until the cylinder weight is constant signifying the presence of oil only.
- The cylinder with only oil is then weighed and recorded.
- Using a suitable solvent, the oil is removed.
- The empty chamber is weighed and recorded.
- The net weights of the refrigerant and the mixture, as well as the oil, are found by differences, and the mixture composition is calculated (to an estimated uncertainty of ±1%).

The temperature, pressure, and liquid level at which the sample was removed are also noted. At this point oil may be injected into the test cell or refrigerant may be added (or vented) to alter the concentration for another set of data.

3-3-9-1-4. MIXTURE CONCENTRATION AND DENSITY DETERMINATION

The actual concentration and the density of the liquid is calculated as follows for each test condition. Since the vapor mass varies along with slight variations in the volume as the temperature and pressure change, this also means that the liquid concentration varies slightly as the temperature and pressure change. Generally, the overall variation in liquid refrigerant concentration as temperature and pressure were changed during any particular test was less than 3%. The vapor density is calculated from known temperature and vapor pressure by a computerized property routine based on work by the National Institute of Standards and Technology [NIST (1993)]. However, it should be noted that any accurate property relation or table could also have been used. With

this density and the vapor volume determined from the level of the vapor-liquid interface, the mass of refrigerant in the vapor is calculated. Since the total mass of oil and refrigerant charged is known, the mass of refrigerant in the liquid is calculated by subtracting the mass of the vapor from the total mass of refrigerant in the cell. A ratio of the mass of refrigerant in the liquid to the total liquid mass determines the resulting liquid composition at each test condition. As noted earlier, the liquid is also sampled at one temperature during each run to check the composition at that test condition. Table 3.2 shows that calculated concentrations agree with concentrations based on sampling.

Table 3.2 Comparison of calculated concentrations and sampled concentrations

R-236fa/Castrol SW-68		R-236fa/Mobil Arctic-46	
Concentration (%)		Concentration (%)	
Calculated	Sampled	Calculated	Sampled
15	16	15	14
25	26	20	21
40	40	25	26
-	-	35	36

With the known masses of oil and refrigerant and the observed level of the liquid, the liquid densities are calculated for each test point. It should be noted that these densities are determined from test data and are not calculated using the ideal mixing assumption. As a point of comparison, the liquid density at the sampling temperature is also determined from the net mass of the liquid sample and the known volume of the sampling chamber.

3-3-9-2. EXPERIMENTAL PROCEDURES

After the temperature, composition, pressure, liquid viscosity and density are determined for each data point, a useful and convenient presentation of the results follows from the development of the correlating equations. The following section presents a discussion of the techniques which were used to derive coefficients for the empirical correlating equations used to represent the data.

3-3-9-2-1. DATA REDUCTION

Calculations required to determine the liquid density and composition from observed data at each test condition have been discussed in general terms in a previous section which outlined experimental procedures. A

more detailed discussion of these calculations and the associated uncertainties, illustrated by using an example test condition, is provided in a publication by Van Gaalen et al. (1991a).

3-3-9-2-2. DATA CORRELATION EQUATIONS

After all the data have been compiled into one file, a nonlinear regression analysis is performed to determine the best set of coefficients for each of the following empirical equations. These equations can be used to reproduce the data or to interpolate results at intermediate states for which data were not directly obtained. It should be noted that these equations are empirical fits of the data and are not based on theoretical considerations.

$$\log_{10}\mu = A_0 + A_1C + A_2\theta + A_3C\theta + A_4C^2 + A_5C^2\theta + A_6C\theta^2 + A_7\theta^2 + A_8C^2\theta^2 \qquad (1)$$

$$P = B_0 + B_1C + B_2\theta + B_3C\theta + B_4C^2 + B_5C^2\theta + B_6C\theta^2 + B_7\theta^2 + B_8C^2\theta^2 \qquad (2)$$

$$\rho L = D_0 + D_1C + D_2\theta + D_3C\theta + D_4C^2 + D_5C^2\theta + D_6C\theta^2 + D_7\theta^2 + D_8C^2\theta^2 \qquad (3)$$

where

A_0, A_1, A_2, A_3, A_4, A_5, A_6, A_7, A_8 are constant coefficients in Equation 1 (units vary depending on term)

B_0, B_1, B_2, B_3, B_4, B_5, B_6, B_7, B_8 are constant coefficients in Equation 2 (units vary depending on term)

D_0, D_1, D_2, D_3, D_4, D_5, D_6, D_7, D_8 are constant coefficients in Equation 3 (units vary depending on term)

C = the mass fraction of refrigerant in the liquid (%)

θ = nondimensional temperature equaling the temperature in K divided by the reference temperature of 293.15K.

μ = nondimensional viscosity (viscosity in centipoise divided by one centipoise)

P = the absolute pressure, MPa

ρL = the density of the liquid, g/cm^3

Although the above equations are nonlinear, they are linearized using the following variable substitutions in order to make use of a general purpose multivariate linear regression algorithm to determine the coefficients:

$X_1 = C$; $X_2 = \theta$; $X_3 = C\theta$; $X_4 = C^2$;

$X_5 = C^2\theta$; $X_6 = C\theta^2$; $X_7 = \theta^2$; $X_8 = C^2\theta^2$

The resulting equations are linear in the eight variables X_1 through X_8. For example,

$$\log_{10}\mu = A_0 + A_1X_1 + A_2X_2 + A_3X_3 + A_4X_4 + A_5X_5 + A_6X_6 + A_7X_7 + A_8X_8 \tag{4}$$

The linear regression algorithm is performed using Statistical Analysis System [SAS (1993)] software. SAS provides statistical information about the significance of each of the coefficients in the above equations. It also used to calculate regression coefficients as an indication of the overall goodness of fit of each equation. Tables, 4.6 and 4.11 listing the coefficients obtained from the Stastical Analysis System are to be presented later. Those tables also list the standard error and the probability (Prob > |T|). This probability provides an indication of empirical significance level (P-value) of the coefficients. It is important to note that the resulting equations are empirical fits of data and are not based on theoretical considerations. Also, some of the coefficients which do not significantly contribute to the correlation are omitted to provide a more useful and simpler equation.

3-4. SUMMARY OF SOLUBILITY, VISCOSITY, AND DENSITY TEST FACILITY

A lubricant/refrigerant test facility has been described which can provide critically needed viscosity, solubility, and density data for a variety of lubricant/refrigerant mixtures over a range of pressures and temperatures. The facility used instrument test cells for observation of the contents. This test facility could be used for determination of the solubility, viscosity, and density of lubricant/refrigerant mixtures with refrigerant compositions ranging from 0 to 40 %. The operating temperatures of the test facility ranged from 30 to 100°C (86 to 212°F). The operating pressure ranged from 0 to 3.5 MPa (0 to 500 psia).

Experimental procedures and data reduction techniques, including the correlating equations, have been outlined. Data obtained with this test facility for the mixtures of R-236fa and two different lubricants are presented in the following chapter.

CHAPTER 4

R-236fa/LUBRICANT PROPERTY RESULTS

4-1. MISCIBILITY RESULTS FOR R-236fa/LUBRICANT MIXTURES

This section presents results of miscibility measurements for each of two different lubricants with R-236fa. The raw data are presented and also summarized. Results of the measurements of R-236fa with each lubricant are presented below. For every refrigerant/lubricant combination investigated, the data set consists of the concentration, temperature, and visual characteristics of the contents of the cell.

Two different lubricants from different manufacturers and with different viscosities were used in this study. Both lubricants were POE's. Table 4.1 provides important characteristics of the two lubricants, such as viscosity, density, pour point, and flash point. Table 4.2 provides the miscibility test results for each R-236fa/lubricant pair. The two refrigerant/lubricant pairs were found to be completely miscible over the temperature range tested, -40 to 90°C (-40 to 194°F), and refrigerant concentration range, about 25 to 85%.

Table 4.1. Lubricant characteristics

Type of lubricant	Lubricant (viscosity) trade name	Viscosity cSt	Density g/cm^3	Pour Point (°C)	Flash Point (°C)
Polyol ester (POE)	Pentaerythritol mixed acid (ISO68) Castrol SW-68	44.3@40°C 6.8@100°C	0.976@ 15.6°C	-45.0	241
Polyol ester (POE)	Pentaerythritol mixed acid (ISO46) Mobil Arctic-46	68.0@40°C 8.8@100°C	0.980@ 20.0°C	-39.0	250

4-2. SOLUBILITY, VISCOSITY, AND DENSITY RESULTS FOR R-236fa/LUBRICANT MIXTURES

For every refrigerant/lubricant mixture tested, the data set at each nominal liquid composition consists of temperature, pressure, concentration, absolute viscosity, and density values for a series of test points.

Table 4.2. Miscibility raw data for R-236fa/Castrol SW-68 and R-236fa/Mobil Arctic-46 mixtures

	Refrigerant mass fraction (1)					
Oil name	Castrol SW-68			Mobil Arctic-46		
Temp(°C)	0.274	0.541	0.826	0.292	0.58	0.847
90.46	clear (2)	clear	clear	clear	clear	clear
80.06	clear	clear	clear	clear	clear	clear
69.96	clear	clear	clear	clear	clear	clear
59.78	clear	clear	clear	clear	clear	clear
49.97	clear	clear	clear	clear	clear	clear
40.02	clear	clear	clear	clear	clear	clear
30.06	clear	clear	clear	clear	clear	clear
19.95	clear	clear	clear	clear	clear	clear
10.01	clear	clear	clear	clear	clear	clear
-0.11	clear	clear	clear	clear	clear	clear
-10.20	clear	clear	clear	clear	clear	clear
-20.07	clear	clear	clear	clear	clear	clear
-30.02	clear	clear	clear	clear	clear	clear
-40.05	clear	clear	clear	clear	clear	clear

Notes: (1) Mass fraction is the mass of refrigerant divided by the total mass of the mixture.

(2) Clear refers to the presence of a single phase only and that the mixture is miscible.

The data for each nominal concentration tested is then correlated into a complete data set for each lubricant/refrigerant mixture pair. As mentioned before. a non-linear multi-regression analysis is performed on a data set to find the best set of coefficients of the correlating equation. The results of the regression are then presented graphically, as well as in the form of the empirical correlations.

The results of viscosity, solubility. and density measurements for R-236fa with two lubricants are presented in the following order:

- Lubricant characteristics.
- Sample experimental raw data.
- Results of the multi-regression analysis in the forms of coefficients for empirical equations.
- Correlations used to develop solubility. viscosity. and density charts and tables.
- Complete sets of experimental data.

4-2-1. R-236fa WITH CASTROL SW-68

4-2-1-1. RAW DATA

Table 4.3 through Table 4.5 provide complete listings of the experimental data for solubility, viscosity, and density for R-236fa with lubricant Castrol SW-68 solutions. These tables show that for mixtures of R-236fa with Castrol SW-68 the solubility, viscosity, and density each is a function of temperature and concentration. For the R-236fa/Castrol SW-68 mixtures, (1) the solubility increases with increasing temperature and with increasing refrigerant concentration (i.e., mass fraction of refrigerant), (2) the viscosity decreases with increasing temperature and with increasing refrigerant concentration, and (3) the density decreases with increasing temperature but increases with increasing refrigerant concentration.

The solubility table is tabulated with saturated vapor pressure and temperature for various concentrations of R-236fa in the liquid mixture. The viscosity table is tabulated with dynamic viscosity and temperature for various concentrations of R-236fa in the liquid mixture. Also, the density table is tabulated with liquid density and vapor density versus temperature for various concentrations of liquid mixture.

Table 4.3 shows that for a nominal concentration the vapor pressure increases with increasing temperature and with increasing refrigerant concentration. Table 4.4 shows that for a nominal concentration the dynamic viscosity decreases with increasing temperature and with increasing refrigerant concentration. Table 4.5 shows that for a nominal concentration the density decreases with increasing temperature and increases with increasing refrigerant concentration.

4-2-1-2. CORRELATING EQUATIONS

The coefficients for the correlating equations (Equations 1 to 3 in Section 3-3-9-2-2) as derived for R-236fa with lubricant Castrol SW-68 are given in Table 4.6.

It is important to note that, when using the correlations in lieu of the graphs, special care must be taken to avoid extrapolation beyond the limits of applicability. These limits of applicability are given, along with the correlating coefficients, in Table 4.6.

4-2-1-3. TABULAR RESULTS

Values for solubility, dynamic viscosity, kinematic viscosity, and density can be obtained by using the correlating equations described earlier. These "correlated (smoothed) data" are sometimes (such as when using a computer) more useful than selecting values from a graph. Table 4.7 provides "smoothed data" for R-236fa/Castrol SW-68 mixtures.

4-2-1-4. GRAPHICAL RESULTS

Property plots for solubility, dynamic viscosity, kinematic viscosity, and density can be developed by using the correlating equations described earlier. Graphical results for the solubility, dynamic viscosity, kinematic viscosity, and density of R-236fa and Castrol SW-68 mixtures are given in Figures 4.1 through 4.4, respectively.

Table 4.3. Experimental solubility data for R-236fa and Castrol SW-68 lubricant solutions

Temperature (°C)	Saturated vapor pressure (kPa)	Refrigerant concentration (mass fraction)
106.42	0.0	0.000
97.46	0.0	0.000
86.05	0.0	0.000
75.97	0.0	0.000
65.49	0.0	0.000
55.50	0.0	0.000
46.94	0.0	0.000
41.82	0.0	0.000
45.79	0.0	0.000
42.34	0.0	0.000
107.67	127.57	0.201
97.40	126.21	0.200
86.72	120.18	0.200
76.24	109.77	0.201
66.46	89.48	0.204
56.03	72.12	0.207
50.17	65.98	0.208
44.92	59.42	0.209
36.36	52.52	0.210
107.41	195.87	0.304
97.52	185.72	0.304
87.06	157.46	0.306
75.79	139.38	0.308
65.91	116.66	0.310
53.30	82.99	0.314
44.05	76.72	0.315
35.63	65.93	0.316
35.91	65.64	0.316
107.93	303.55	0.443
97.52	266.52	0.444
87.64	227.90	0.445
76.60	172.94	0.449
66.60	139.87	0.451
55.19	108.70	0.452
46.14	88.71	0.454
41.65	79.97	0.454
42.49	81.45	0.454

Table 4.4. Experimental dynamic viscosity data for R-236fa and Castrol SW-68 lubricant solutions

Temperature (°C)	Dynamic viscosity (cP)	Refrigerant concentration (mass fraction)
98.62	7.55	0.000
92.20	9.00	0.000
81.68	12.22	0.000
72.78	18.72	0.000
63.93	26.09	0.000
55.79	37.06	0.000
49.70	48.50	0.000
45.58	59.18	0.000
48.00	52.20	0.000
46.45	56.21	0.000
100.76	3.59	0.201
92.22	4.37	0.200
82.95	5.54	0.200
74.28	7.01	0.201
66.70	8.62	0.204
58.14	11.18	0.207
51.83	13.39	0.208
46.81	17.05	0.209
40.38	22.55	0.210
99.92	2.25	0.304
91.92	2.67	0.304
83.19	3.25	0.306
73.10	4.16	0.308
65.42	5.07	0.310
53.62	6.83	0.314
47.48	8.21	0.315
40.42	10.39	0.316
40.62	10.30	0.316
100.67	1.18	0.443
92.30	1.41	0.444
84.55	1.67	0.445
75.21	2.05	0.449
65.49	2.55	0.451
54.29	3.43	0.452
44.25	4.54	0.454
39.46	5.22	0.454
40.30	5.09	0.454

Table 4.5. Experimental density data for R-236fa and Castrol SW-68 lubricant solutions

Temperature (°C)	Density (g/cm^3)	R-236fa concentration (mass fraction)	Vapor Density (g/cm^3)
101.48	0.804	0.000	0.000
93.66	0.808	0.000	0.000
82.86	0.816	0.000	0.000
73.16	0.820	0.000	0.000
63.53	0.826	0.000	0.000
54.84	0.832	0.000	0.000
47.37	0.836	0.000	0.000
43.42	0.839	0.000	0.000
46.32	0.839	0.000	0.000
44.27	0.839	0.000	0.000
102.65	1.027	0.201	0.047
93.03	1.035	0.200	0.049
82.98	1.044	0.200	0.048
73.29	1.053	0.201	0.046
64.57	1.063	0.204	0.038
55.02	1.073	0.207	0.031
49.52	1.077	0.208	0.029
44.61	1.081	0.209	0.026
37.49	1.069	0.210	0.024
102.53	1.068	0.304	0.079
93.52	1.078	0.304	0.078
83.76	1.087	0.306	0.067
72.88	1.100	0.308	0.062
63.92	1.109	0.310	0.052
51.84	1.122	0.314	0.037
43.70	1.131	0.315	0.035
36.16	1.140	0.316	0.030
36.65	1.137	0.316	0.030
102.90	1.122	0.443	0.146
93.09	1.137	0.444	0.131
84.81	1.147	0.445	0.114
74.57	1.164	0.449	0.082
64.08	1.177	0.451	0.066
51.19	1.186	0.452	0.050
40.65	1.196	0.454	0.041
35.37	1.210	0.454	0.037
36.40	1.205	0.454	0.038

Table 4.6. Coefficients for empirical correlations of property data for R-236fa/Castrol SW-68 mixtures

Note: The limits of applicability of the correlations are
Composition (X): 0 to 45 weight percent refrigerant
Temperature: 30 to 100°C (86 to 212°F)

Solubility (kPa)			
Term	Coefficient	Standard Error	Prob. > |T|
Intercept	B_0= 0.0		
C	B_1= -83.266342	21.28777032	0.0005
θ	B_2= 0.0		
$C\theta$	B_3= 139.213041	36.36123530	0.0006
C^2	B_4= 249.945401	56.49952550	0.0001
$C^2\theta$	B_5= -444.429997	96.41900600	0.0001
$C\theta^2$	B_6= -55.312753	15.46471128	0.0012
θ^2	B_7= 0.0		
$C^2\theta^2$	B_8= 194.751213	40.97263435	0.0001

Viscosity (cP)			
Term	Coefficient	Standard Error	Prob. > |T|
Intercept	A_0= 16.941667	1.87488185	0.0001
C	A_1= -19.847644	6.02399756	0.0026
θ	A_2= -21.633982	3.20722086	0.0001
$C\theta$	A_3= 22.767335	10.28738177	0.0349
C^2	A_4= 0.0		
$C^2\theta$	A_5= 7.401082	1.36791442	0.0001
$C\theta^2$	A_6= -6.442886	1.40145683	0.0154
θ^2	A_7= 7.068495	1.55413777	0.0001
$C^2\theta^2$	A_8= -6.445285	1.33000535	0.0001

Density (g/cm³)			
Term	Coefficient	Standard Error	Prob. > |T|
Intercept	D_0= 0.914702	0.01246634	0.0001
C	D_1= 1.349341	0.02952514	0.0001
θ	D_2= 0.0		
$C\theta$	D_3= 0.0		
C^2	D_4= 0.0		
$C^2\theta$	D_5= -1.144070	0.05614224	0.0001
$C\theta^2$	D_6= 0.0		
θ^2	D_7= -0.064982	0.00883297	0.0001
$C^2\theta^2$	D_8= 0.0		

Table 4.7 Smoothed data for R-236fa/Castrol SW-68 mixtures

Temp. (° C)	Refrigerant Concentration (mass fraction)	Density (g/cm³)	Viscosity Dynamic (cP)	Kinematic (cSt)	Saybolt (SUS)	Pressure (kPa)	(psia)
30	0.00	0.845	134.48	159.11	736.5	0.00	0.00
40	0.00	0.841	79.00	93.98	435.7	0.00	0.00
50	0.00	0.836	48.19	57.67	268.2	0.00	0.00
60	0.00	0.831	30.54	36.76	172.4	0.00	0.00
70	0.00	0.826	20.10	24.34	116.9	0.00	0.00
80	0.00	0.820	13.74	16.74	84.7	0.00	0.00
90	0.00	0.815	9.75	11.96	66.2	0.00	0.00
100	0.00	0.809	7.19	8.88	55.4	0.00	0.00
30	0.10	0.968	65.60	67.75	314.1	140.7	20.40
40	0.10	0.963	41.23	42.80	199.6	206.9	30.01
50	0.10	0.958	26.71	27.98	132.7	264.9	38.42
60	0.10	0.953	18.04	18.93	93.6	314.5	45.61
70	0.10	0.947	12.56	13.26	70.9	355.7	51.59
80	0.10	0.942	9.05	9.61	57.7	388.6	56.36
90	0.10	0.936	6.74	7.20	49.7	413.2	59.93
100	0.10	0.930	5.20	5.59	44.6	429.4	62.28
30	0.20	1.068	33.14	31.04	146.0	253.7	36.80
40	0.20	1.062	22.07	20.79	101.2	362.4	52.56
50	0.20	1.055	15.14	14.35	75.0	463.4	67.22
60	0.20	1.049	10.70	10.20	59.7	556.9	80.77
70	0.20	1.042	7.79	7.47	50.5	642.7	93.22
80	0.20	1.035	5.75	5.64	44.6	720.9	104.56
90	0.20	1.028	4.51	4.38	40.7	791.5	114.79
100	0.20	1.021	3.59	3.51	37.9	854.5	123.93
30	0.30	1.144	17.34	15.16	78.0	339.2	49.20
40	0.30	1.135	12.12	10.68	61.2	466.4	67.64
50	0.30	1.127	8.68	7.70	51.1	595.7	86.40
60	0.30	1.119	6.37	5.70	44.7	727.3	105.48
70	0.30	1.110	4.79	4.32	40.4	861.0	124.87
80	0.30	1.101	3.69	3.35	37.3	996.8	144.58
90	0.30	1.092	2.92	2.67	35.1	1134.9	164.60
100	0.30	1.083	2.36	2.18	33.4	1275.1	184.94
30	0.40	1.196	9.40	7.86	51.5	397.0	57.58
40	0.40	1.185	6.83	5.76	44.8	518.9	75.25
50	0.40	1.174	5.05	4.30	40.2	661.7	95.97
60	0.40	1.162	3.81	3.28	36.9	825.6	119.74
70	0.40	1.151	2.93	2.54	34.6	1010.5	146.56
80	0.40	1.140	2.29	2.01	32.8	1216.4	176.43
90	0.40	1.128	1.82	1.62	31.5	1443.4	209.34
100	0.40	1.116	1.48	1.33	30.5	1691.4	245.31

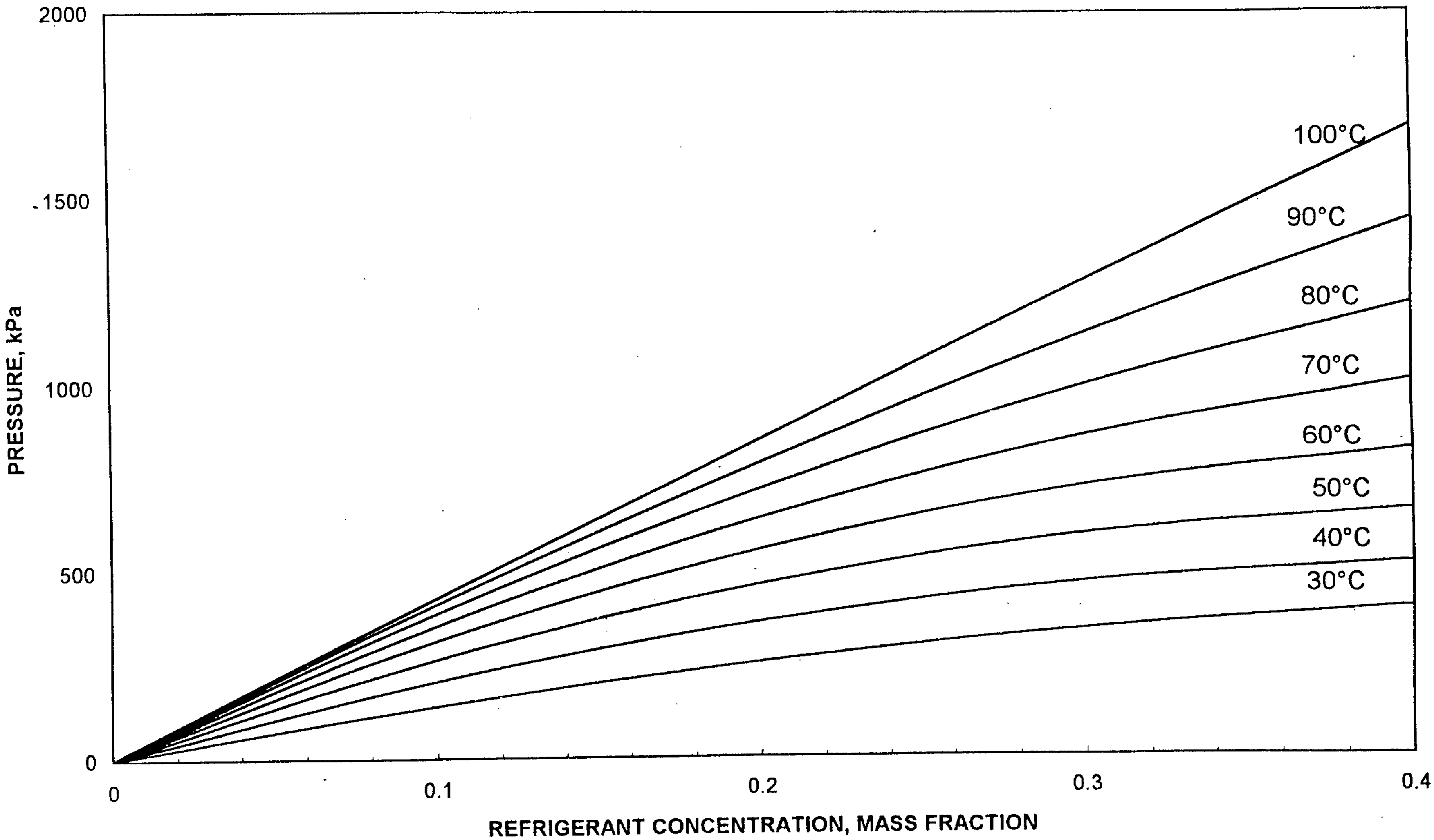

Figure 4.1. Solubility of R-236fa and Castrol SW-68 mixture

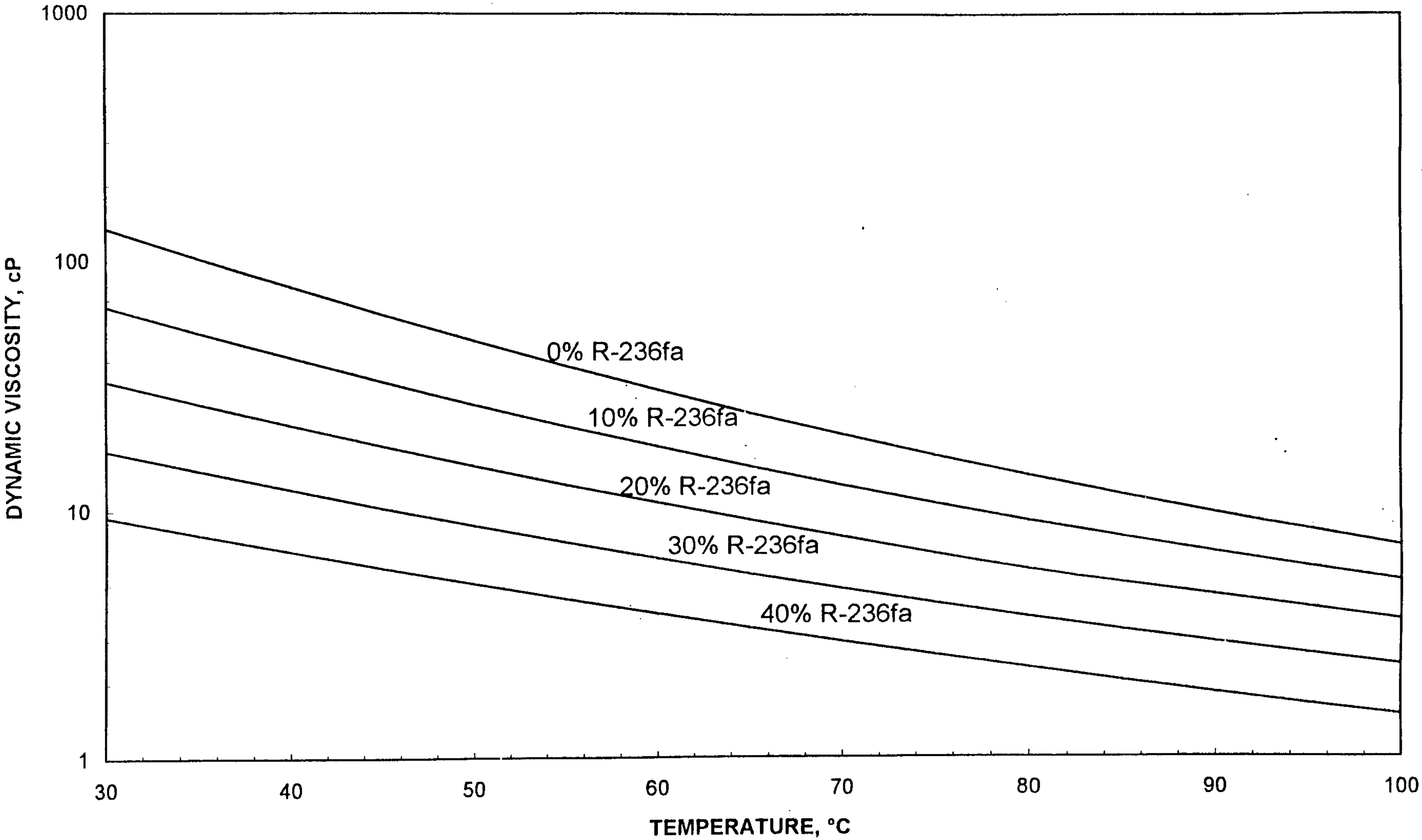

Figure 4.2. Dynamic viscosity of R-236fa and Castrol SW-68 mixture

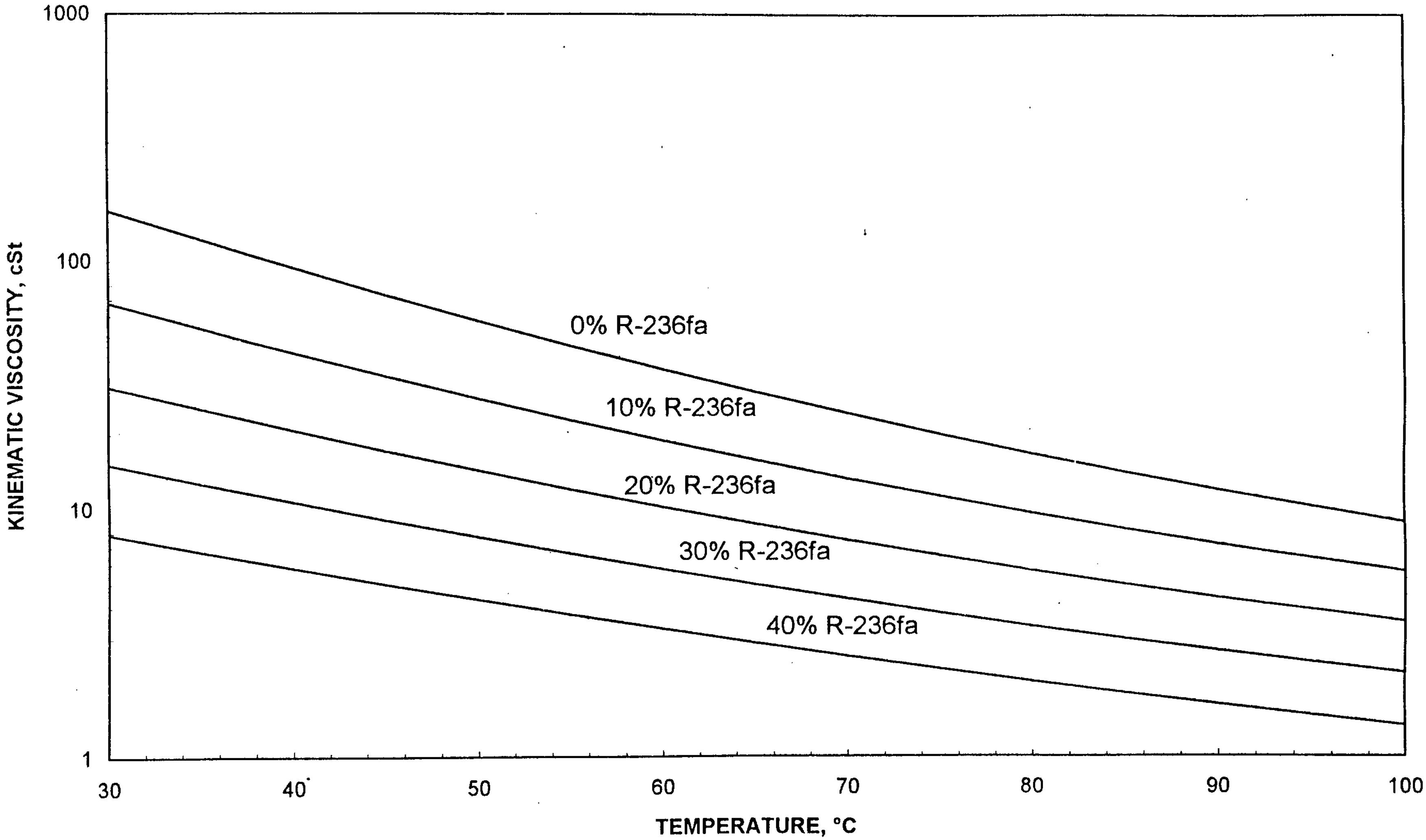

Figure 4.3. Kinematic viscosity of R-236fa and Castrol SW-68 mixture

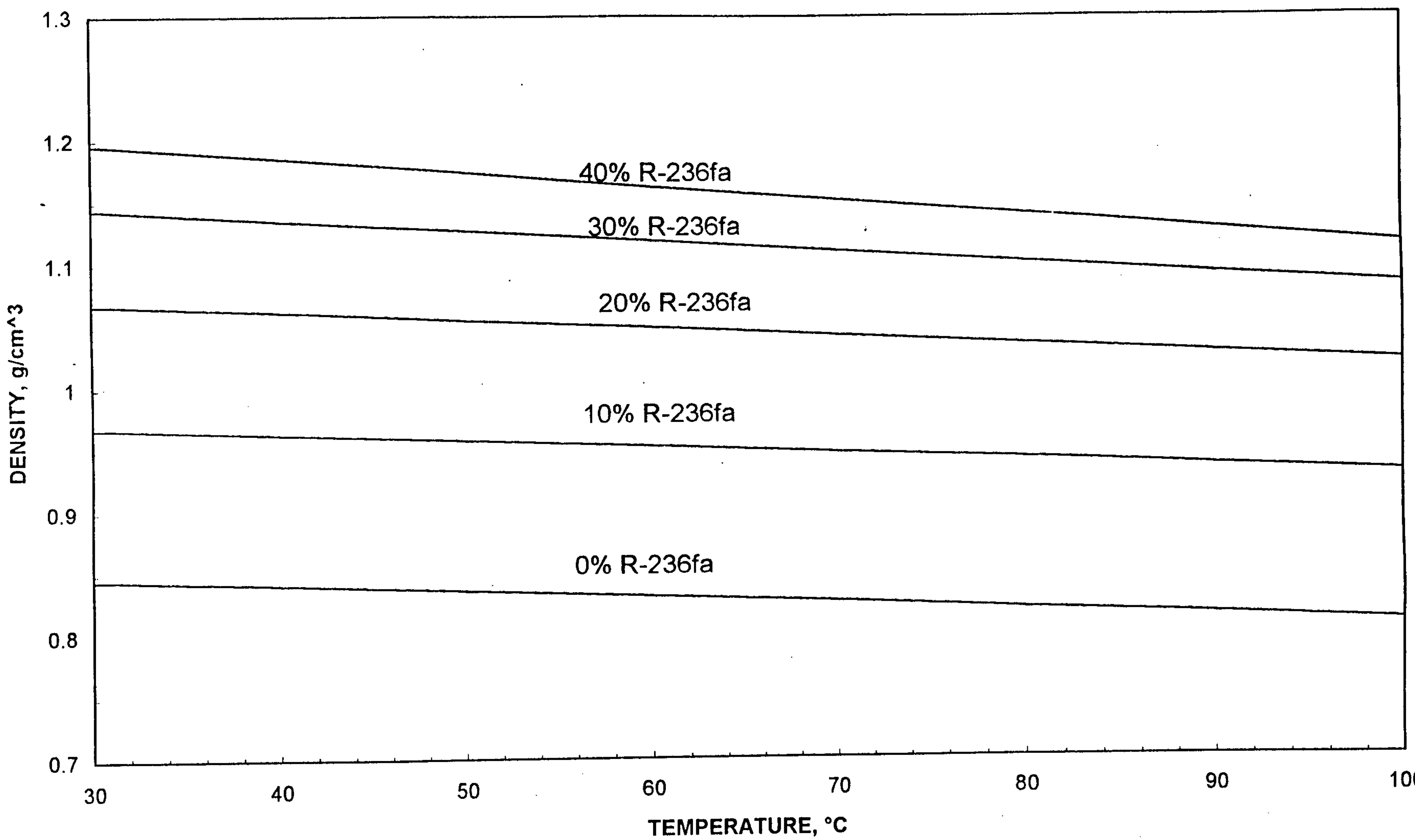

Figure 4.4. Density of R-236fa and Castrol SW-68 mixture

The plot of pressure versus refrigerant concentration for a range of temperatures shows that the pressure increases with increasing refrigerant concentration and temperature. The plot of dynamic viscosity versus temperature for a range of refrigerant concentrations shows that the dynamic viscosity decreases with increasing refrigerant concentration and temperature. The plot of kinematic viscosity versus temperature for a range of refrigerant concentrations shows that the kinematic viscosity decreases with increasing refrigerant concentration and temperature. The plot of density versus temperature for a range of refrigerant concentrations shows that the density increases with increasing refrigerant concentration and decreases with increasing temperature.

4-2-2. R-236fa WITH MOBIL ARCTIC-46

4-2-2-1. RAW DATA

Table 4.8 through Table 4.10 provides complete listings of the experimental data for solubility, viscosity, and density for R-236fa and lubricant Mobil Arctic-46 solutions. These tables show that for mixtures of R-236fa with lubricant Mobil Arctic-46 the solubility, viscosity, and density each is a function of temperature and concentration. For the R-236fa/ Mobil Arctic-46 mixtures (1) the solubility increases with increasing temperature and with increasing refrigerant concentration (i.e., mass fraction of refrigerant), (2) the viscosity decreases with increasing temperature and with increasing refrigerant concentration, and (3) the density decreases with increasing temperature but increases with increasing refrigerant concentration.

The solubility table is tabulated with saturated vapor pressure and temperature for various concentrations of R-236fa in the liquid mixture. The viscosity table is tabulated with dynamic viscosity and temperature for various concentrations of R-236fa in the liquid mixture. Also, the density table is tabulated with liquid density and vapor density versus temperature for various refrigerant concentrations in the liquid mixture.

Table 4.8 shows that for a nominal refrigerant concentration the vapor pressure increases with increasing temperature and with increasing refrigerant concentration. Table 4.9 shows that for a nominal refrigerant concentration the dynamic viscosity decreases with increasing temperature and with increasing refrigerant concentration. Table 4.10 shows that for a nominal refrigerant concentration the density decreases with increasing temperature and increases with increasing refrigerant concentration.

4-2-2-2. CORRELATING EQUATIONS

The coefficients for the correlating equations (Equations 5 to 7) as derived for R-236fa with lubricant Mobil Arctic-46 are given in Table 4.11.

$$\log_{10}\mu = A_0 + A_1C + A_2\theta + A_3C\theta + A_4C^2 + A_5C^2\theta + A_6C\theta^2 + A_7\theta^2 + A_8C^2\theta^2 \tag{5}$$

$$P = B_0 + B_1C + B_2\theta + B_3C\theta + B_4C^2 + B_5C^2\theta + B_6C\theta^2 + B_7\theta^2 + B_8C^2\theta^2 \tag{6}$$

$$\rho L = D_0 + D_1C + D_2\theta + D_3C\theta + D_4C^2 + D_5C^2\theta + D_6C\theta^2 + D_7\theta^2 + D_8C^2\theta^2 \tag{7}$$

It is important to note that. when using the correlations in lieu of the graphs. special care must be taken to avoid extrapolation beyond the limits of applicability. These limits of applicability are given, along with the correlating coefficients. in Table 4.11.

4-2-2-3. TABULAR RESULTS

Values for solubility. dynamic viscosity. kinematic viscosity, and density can be obtained by using the correlating equations described earlier. These "correlated (smoothed) data" are sometimes (such as when using a computer) more useful than selecting values from a graph. Table 4.12 provides "smoothed data" for R-236fa/Mobil Arctic-46 mixtures.

4-2-2-4. GRAPHICAL RESULTS

Property plots for solubility, dynamic viscosity, kinematic viscosity, and density can be developed by using the correlating equations described earlier. Graphical results for the solubility, dynamic viscosity. kinematic viscosity. and density of R-236fa and Mobil Arctic-46 mixtures are given in Figures 4.5 through 4.8. respectively. The plot of pressure versus refrigerant concentration for a range of temperatures shows that the pressure increases with increasing refrigerant concentration and temperature. The plot of dynamic viscosity versus temperature for a range of refrigerant concentrations shows that the dynamic viscosity decreases with increasing refrigerant concentration and temperature. The plot of kinematic viscosity versus temperature for a range of refrigerant concentrations. shows that the kinematic viscosity decreases with increasing refrigerant concentration and temperature. The plot of density versus temperature for a range of refrigerant concentrations. shows that the density increases with increasing refrigerant concentration and decreases with increasing temperature.

Table 4.8. Experimental solubility data for R-236fa and Mobil Arctic-46 lubricant solutions

Temperature (°C)	Saturated vapor pressure (kPa)	Refrigerant concentration (mass fraction)
108.70	0.0	0.000
96.66	0.0	0.000
86.58	0.0	0.000
76.91	0.0	0.000
66.52	0.0	0.000
57.89	0.0	0.000
47.61	0.0	0.000
38.11	0.0	0.000
41.43	0.0	0.000
111.95	872.38	0.129
97.55	783.12	0.130
87.03	672.83	0.133
76.49	566.47	0.136
66.15	456.87	0.139.
55.88	362.23	0.142
46.31	303.22	0.144
36.79	252.56	0.145
39.59	265.73	0.145
107.93	1332.22	0.249
97.63	1135.14	0.253
87.11	944.90	0.256
75.88	770.85	0.259
66.71	676.48	0.261
56.50	533.38	0.264
46.06	428.61	0.266
36.52	349.20	0.268
38.02	362.50	0.267
106.79	1664.87	0.365
96.60	1521.84	0.366
87.01	1278.24	0.368
76.24	981.98	0.372
65.13	780.84	0.374
55.09	631.47	0.376
43.06	483.82	0.377
38.37	424.40	0.378
40.06	444.81	0.378

Table 4.9. Experimental dynamic viscosity data for R-236fa and Mobil Arctic-46 lubricant solutions

Temperature (°C)	Dynamic viscosity (cP)	Refrigerant concentration (mass fraction)
94.25	6.34	0.000
89.40	7.35	0.000
81.17	9.31	0.000
74.34	11.45	0.000
66.41	14.85	0.000
60.30	18.47	0.000
51.06	30.09	0.000
43.13	42.75	0.000
45.81	37.80	0.000
101.30	3.06	0.129
90.13	4.02	0.130
81.64	4.87	0.133
73.30	6.02	0.136
65.42	7.46	0.139
57.80	9.55	0.142
50.72	11.41	0.144
41.39	14.77	0.145
43.21	16.32	0.145
98.26	1.97	0.249
90.31	2.33	0.253
81.83	2.82	0.256
72.26	3.45	0.259
66.29	3.96	0.261
58.47	4.77	0.264
50.14	6.27	0.266
41.97	7.89	0.268
42.96	8.54	0.267
88.62	1.50	0.365
81.23	1.79	0.366
76.32	1.96	0.368
69.72	2.27	0.372
61.27	2.76	0.374
55.23	3.28	0.376
45.88	4.25	0.377
41.85	4.73	0.378
42.63	4.55	0.378

Table 4.10. Experimental density data for R-236fa and Mobil Arctic-46 lubricant solutions

Temperature (°C)	Density (g/cm^3)	R-236fa concentration (mass fraction)	Vapor Density (g/cm^3)
103.12	0.909	0.000	0.000
92.32	0.914	0.000	0.000
83.40	0.920	0.000	0.000
74.39	0.925	0.000	0.000
64.87	0.931	0.000	0.000
57.09	0.937	0.000	0.000
48.25	0.942	0.000	0.000
40.31	0.954	0.000	0.000
44.17	0.948	0.000	0.000
106.09	0.939	0.129	0.046
92.80	0.950	0.130	0.043
83.19	0.958	0.133	0.038
73.54	0.967	0.136	0.033
64.27	0.977	0.139	0.027
54.91	0.987	0.142	0.022
46.24	0.991	0.144	0.019
37.61	0.999	0.145	0.016
40.46	0.996	0.145	0.017
102.70	0.983	0.249	0.078
93.29	0.996	0.253	0.068
83.59	1.006	0.256	0.057
73.10	1.015	0.259	0.047
64.77	1.022	0.261	0.042
55.37	0.032	0.264	0.034
45.74	1.042	0.266	0.028
36.99	1.052	0.268	0.023
38.72	1.047	0.267	0.024
100.27	1.004	0.365	0.106
91.47	1.013	0.366	0.101
83.27	1.026	0.368	0.085
73.48	1.046	0.372	0.064
63.20	1.065	0.374	0.051
53.92	1.076	0.376	0.042
42.71	1.087	0.377	0.032
37.74	1.094	0.378	0.028
39.51	1.089	0.378	0.030

Table 4.11. Coefficients for empirical correlations of property data for R-236fa/Mobil Arctic-46 mixtures

Note: The limits of applicability of the correlations are
Composition (X): 0 to 45 weight percent refrigerant
Temperature: 30 to 100°C (86 to 212°F)

Solubility (kPa)			
Term	Coefficient	Standard Error	Prob. > |T|
Intercept	B_0= 0.0		
C	B_1= 17.600351	6.62858887	0.0124
θ	B_2= 0.0		
$C\theta$	B_3= -44.167950	11.05857874	0.0004
C^2	B_4= 15.918015	4.62284761	0.0017
$C^2\theta$	B_5= -17.353152	3.97363126	0.0001
$C\theta^2$	B_6= 27.802469	4.64460958	0.0001
θ^2	B_7= 0.0		
$C^2\theta^2$	B_8= 0.0		

Viscosity (cP)			
Term	Coefficient	Standard Error	Prob. > |T|
Intercept	A_0= 18.433613	1.99213618	0.0001
C	A_1= -34.793650	9.57355798	0.0011
θ	A_2= -24.933829	3.42499478	0.0001
$C\theta$	A_3= 47.569068	16.23706353	0.0067
C^2	A_4= 13.321006	3.39284726	0.0005
$C^2\theta$	A_5= -10.615702	2.94701827	0.0012
$C\theta^2$	A_6= -17.001064	6.89140372	0.0200
θ^2	A_7= 8.670047	1.46900878	0.0001
$C^2\theta^2$	A_8= 0.0		

Density (g/cm³)			
Term	Coefficient	Standard Error	Prob. > |T|
Intercept	D_0= 1.177392	0.01405050	0.0001
C	D_1= 0.0		
θ	D_2= -0.212733	0.01206858	0.0001
$C\theta$	D_3= 0.288636	0.01335119	0.0001
C^2	D_4= 0.0		
$C^2\theta$	D_5= 2.116699	0.15781451	0.0001
$C\theta^2$	D_6= 0.0		
θ^2	D_7= 0.0		
$C^2\theta^2$	D_8= -1.826845	0.13431580	0.0001

Table 4.12 Smoothed data for R-236fa/Mobil Arctic-46 mixtures

Temp. (° C)	Refrigerant Concentration (mass fraction)	Density (g/cm^3)	Viscosity Dynamic (cP)	Kinematic (cSt)	Saybolt (SUS)	Pressure (kPa)	(psia)
30	0.00	0.957	83.35	87.05	403.2	0.00	0.00
40	0.00	0.950	49.22	51.80	240.9	0.00	0.00
50	0.00	0.943	30.44	32.29	152.0	0.00	0.00
60	0.00	0.936	19.73	21.09	102.7	0.00	0.00
70	0.00	0.928	13.39	14.43	75.4	0.00	0.00
80	0.00	0.921	9.52	10.34	60.3	0.00	0.00
90	0.00	0.914	7.09	7.76	51.6	0.00	0.00
100	0.00	0.907	5.54	6.11	46.2	0.00	0.00
30	0.10	0.990	36.82	37.20	173.9	145.5	21.10
40	0.10	0.983	23.66	24.07	115.3	188.3	27.31
50	0.10	0.976	15.78	16.17	82.2	237.5	34.45
60	0.10	0.969	10.93	11.28	63.5	293.3	42.54
70	0.10	0.962	7.86	8.17	52.8	355.5	51.56
80	0.10	0.955	5.86	6.14	46.2	424.2	61.52
90	0.10	0.948	4.54	4.79	42.0	499.3	72.42
100	0.10	0.941	3.65	3.88	39.1	580.9	84.26
30	0.20	1.027	18.12	17.65	88.0	250.4	36.32
40	0.20	1.019	12.46	12.23	66.9	324.2	47.01
50	0.20	1.011	8.81	8.72	54.5	410.9	59.59
60	0.20	1.003	6.41	6.39	47.0	510.5	74.04
70	0.20	0.995	4.80	4.83	42.0	623.1	90.37
80	0.20	0.987	3.70	3.75	38.6	748.6	108.58
90	0.20	0.978	2.93	2.99	36.1	887.1	128.66
100	0.20	0.969	2.39	2.46	34.4	1038.5	150.62
30	0.30	1.068	9.93	9.30	56.4	314.8	45.65
40	0.30	1.059	7.19	6.79	48.1	407.7	59.13
50	0.30	1.049	5.30	5.06	42.6	519.9	75.41
60	0.30	1.038	3.99	3.84	38.8	651.7	94.51
70	0.30	1.027	3.06	2.98	36.0	802.8	116.43
80	0.30	1.016	2.39	2.35	34.0	973.3	141.17
90	0.30	1.005	1.90	1.89	32.4	1163.2	168.71
100	0.30	0.993	1.55	1.56	31.3	1372.6	199.08
30	0.40	1.114	6.06	5.44	43.8	338.6	49.11
40	0.40	1.102	4.54	4.12	39.6	438.8	63.64
50	0.40	1.088	3.44	3.16	36.5	564.8	81.92
60	0.40	1.074	2.63	2.45	34.2	716.8	103.96
70	0.40	1.059	2.03	1.92	32.4	894.6	129.75
80	0.40	1.044	1.58	1.52	31.1	1098.3	159.29
90	0.40	1.028	1.25	1.21	30.0	1327.8	192.59
100	0.40	1.011	0.99	0.98	29.2	1583.3	229.64

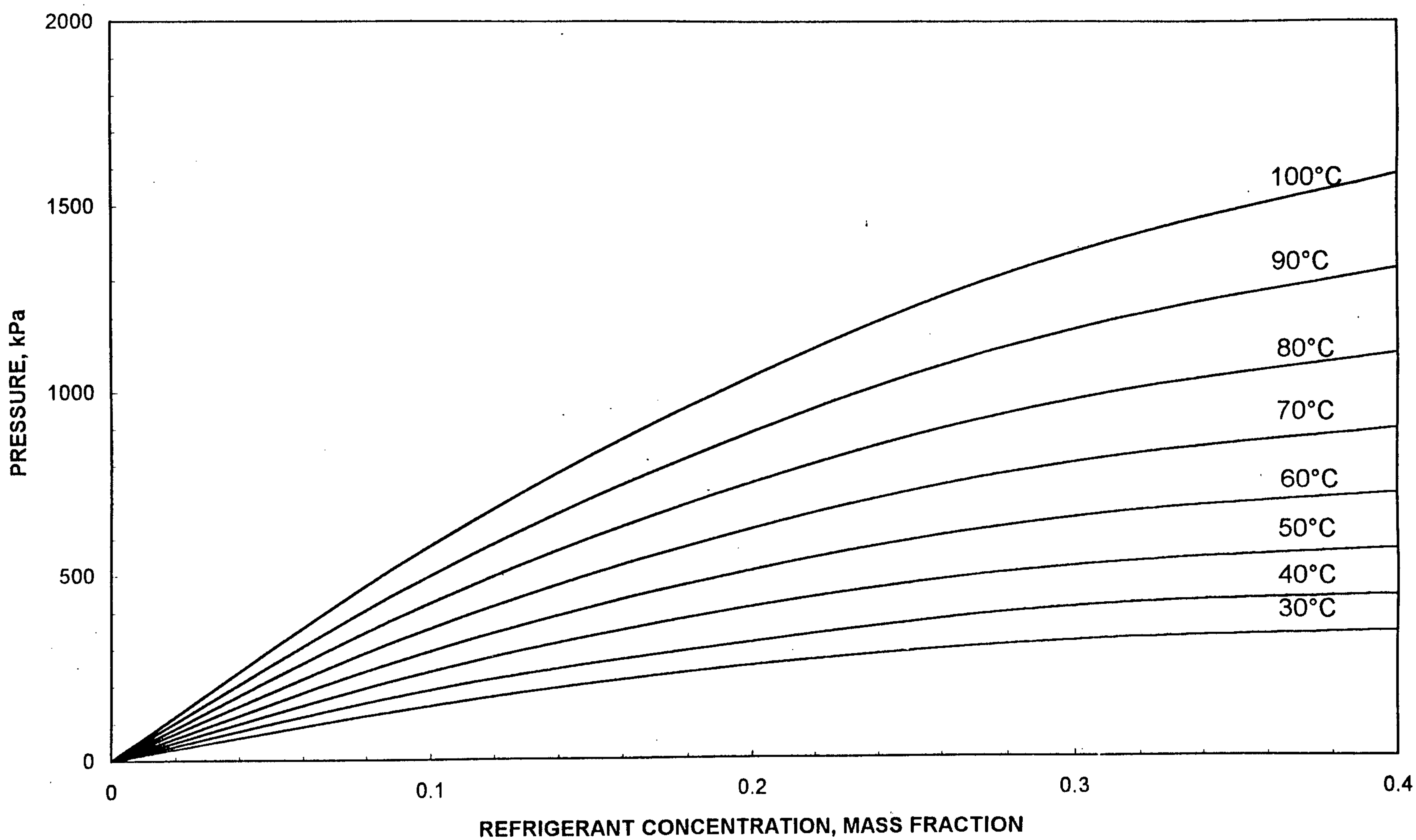

Figure 4.5. Solubility of R-236fa and Mobil Arctic-46 mixture

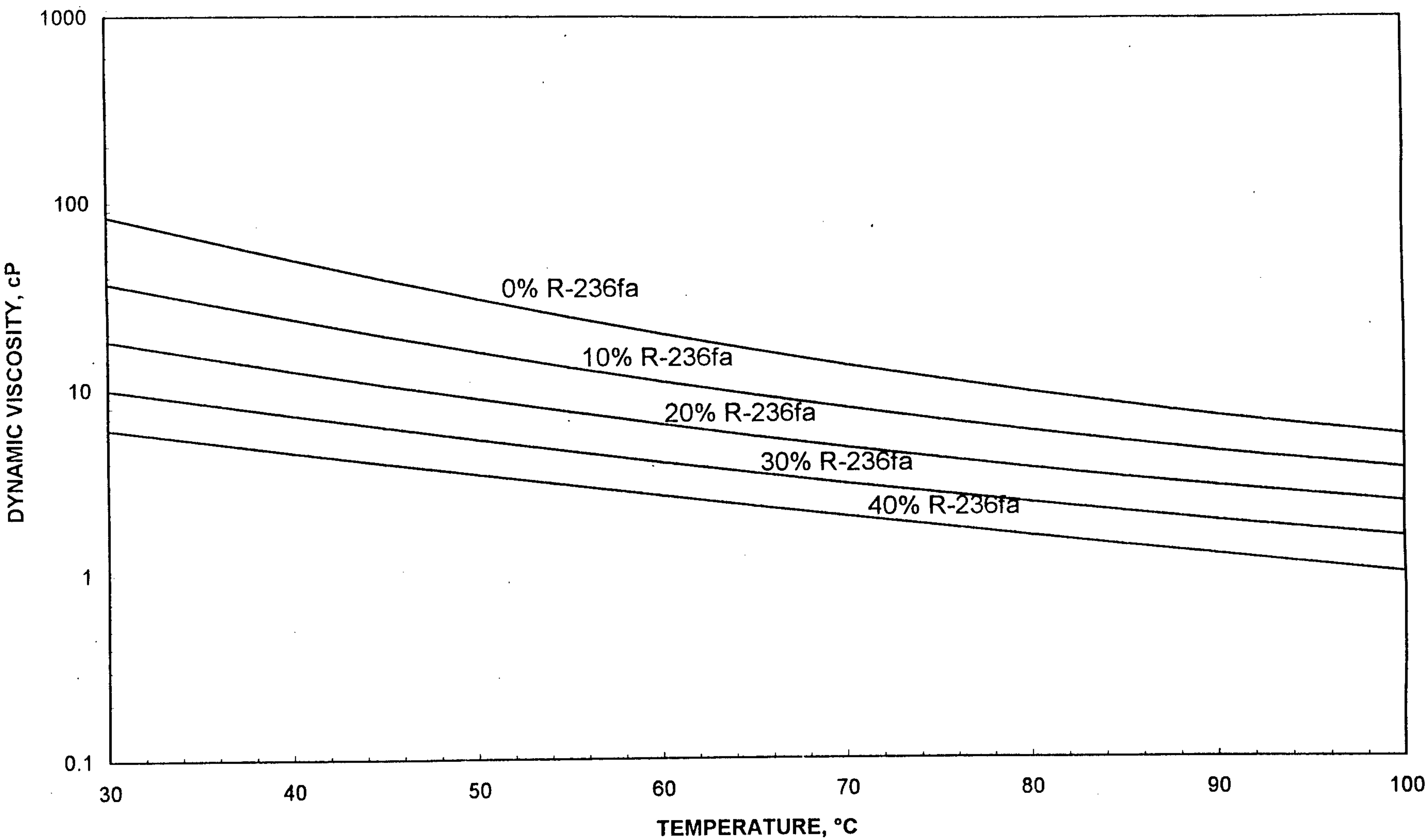

Figure 4.6. Dynamic viscosity of R-236fa and Mobil Arctic-46 mixture

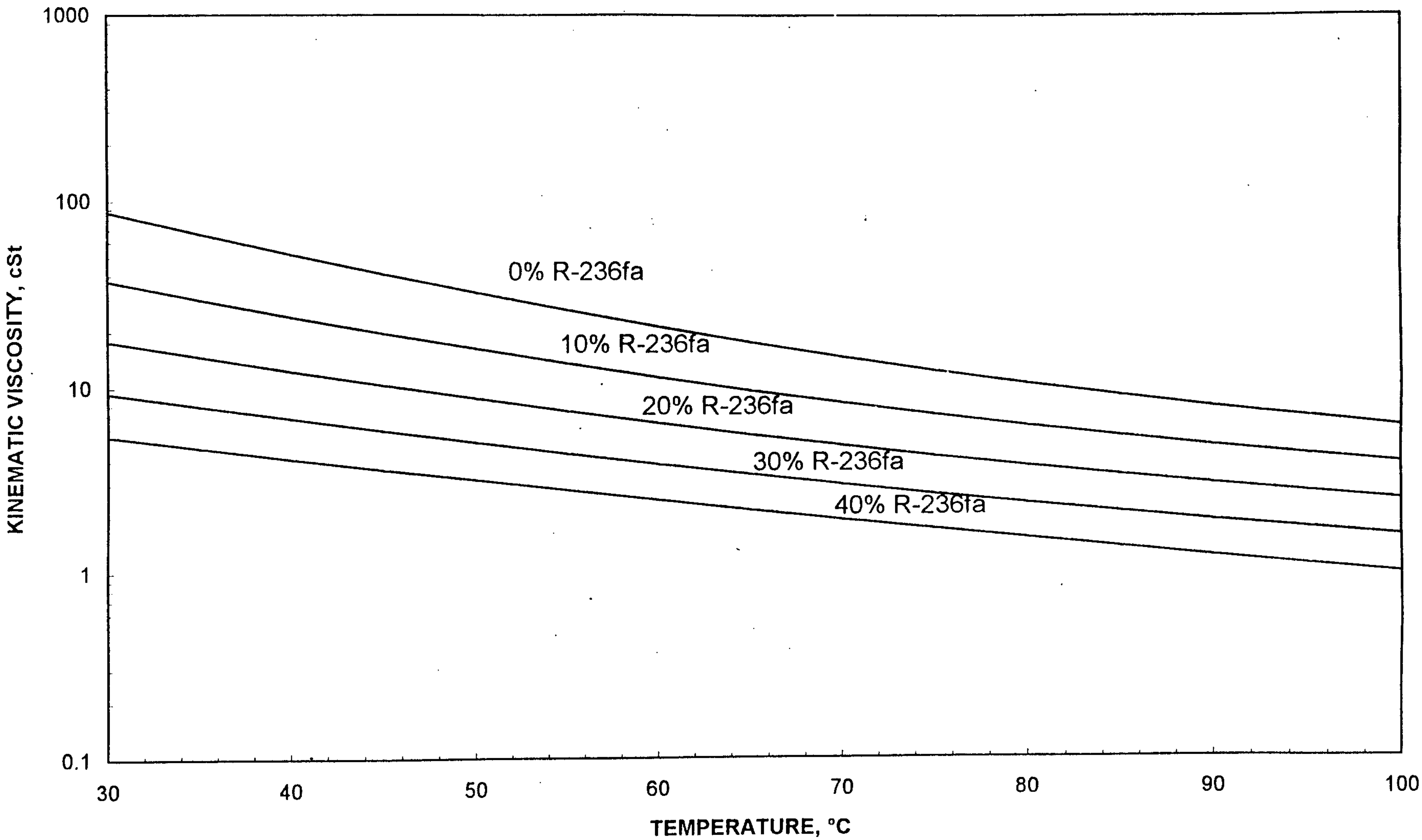

Figure 4.7. Kinematic viscosity of R-236fa and Mobil Arctic-46 mixture

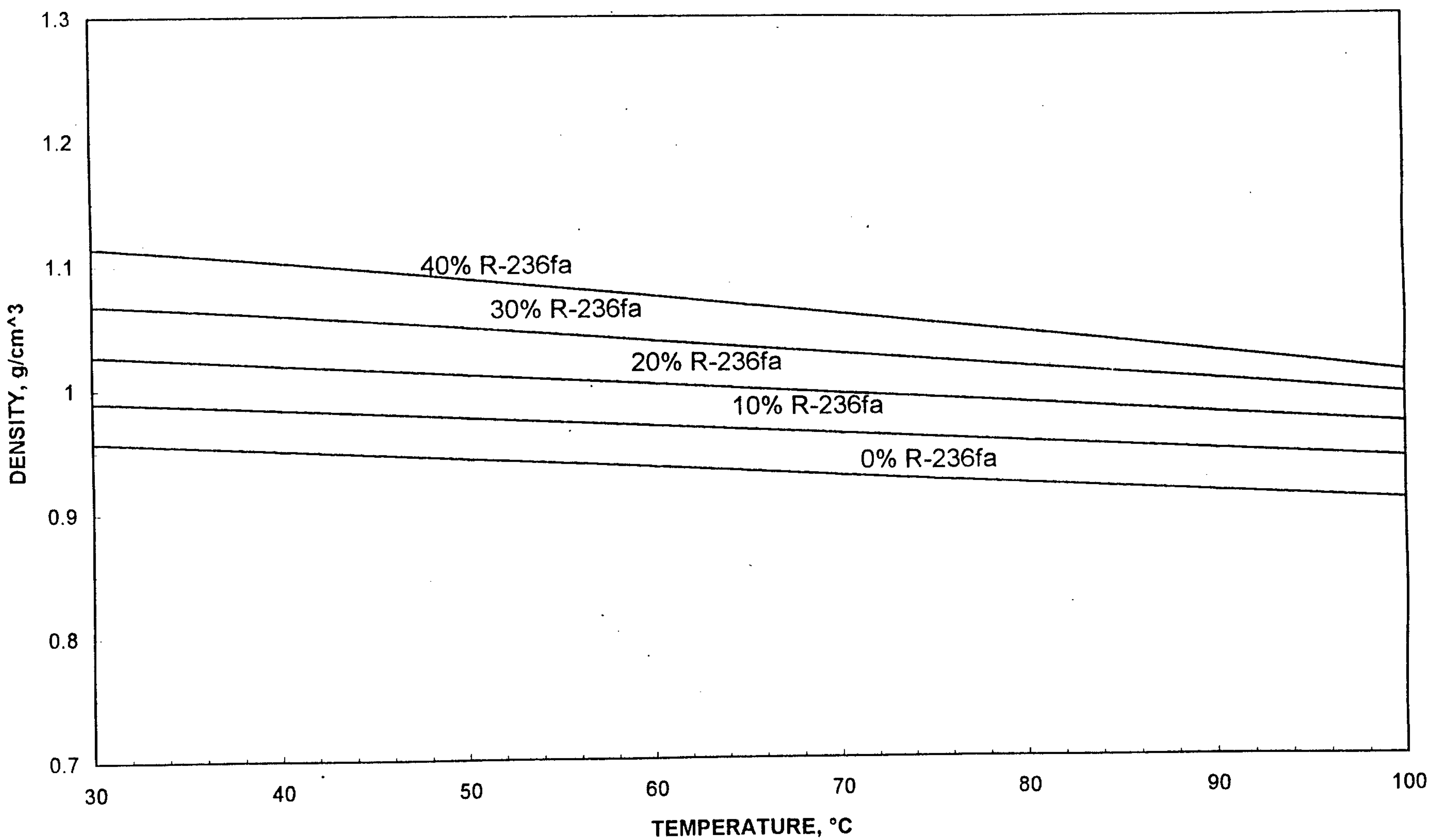

Figure 4.8. Density of R-236fa and Mobil Arctic-46 mixture

4-3. COMPARISON OF R-236fa/CASTROL SW-68 AND R-236fa/MOBIL ARCTIC-46 MIXTURES

This section presents a comparison of miscibility, solubility. viscosity. and density for R-236fa/Castrol-68, and R-236fa/Mobil Arctic-46. The refrigerant/lubricant mixtures are compared at various refrigerant concentrations and temperatures. The purpose of these comparison is to determine whether the non-CFC refrigerant reported in this study (i.e., R-236fa) may be a satisfactory replacement for R-114.

4-3-1. MISCIBILITY

The results of miscibility tests for R-236fa/CASTROL SW-68 and R-236fa/Mobil Arctic-46 mixtures showed that both refrigerant/lubricant mixtures were completely miscible with this lubricant over the temperature and refrigerant concentration ranges tested which were -40 to 90°C (-40 to 194°F) and 25 to 85% (by mass), respectively.

4-3-2. SOLUBILITY, VISCOSITY, AND DENSITY

To better observe the comparison, the compared plots are presented over narrow temperature ranges. Specifically, Figures 4.9 through 4.12 permit comparing the solubility results for R-236fa/Castrol SW-68 and R-236fa/Mobil Arctic-46 mixtures at temperatures ranges of 30 to 40°C. 50 to 60°C. 70 to 80°C, and 90 to 100°C, respectively. In addition to these figures, Table 4.13 gives solubility of each lubricant with R-236fa refrigerant at eight different temperatures, which are 30° C, 40° C, 50° C, 60° C, 70° C, 80° C, 90° C, and 100°C. The pressure of the R-236fa/SW-68 mixture is higher for the temperatures from 30 to 70° C and for a given refrigerant concentration than the pressure of the corresponding R-236fa/Arctic-46 mixture, but at above 80° C temperature. the opposite trend is observed. Table 4.13 tabulates a portion of the data presented graphically in Figures 4.9 through 4.12.

A graphical comparison of the dynamic viscosity for R-236fa/Castrol SW-68 and R-236fa/Mobil Arctic-46 mixtures at 0 to 40 mass percent refrigerant is given in Figure 4.13. In addition to this figure, Table 4.14 compares the dynamic viscosity for the two lubricants with the same refrigerant at five different concentrations, which are 0, 10, 20, 30. and 40% refrigerant concentration. respectively. The dynamic viscosity of the R-236fa/SW-68 mixture is higher than R-236fa/Arctic-46 mixture for a given refrigerant concentrations. Table 4.14 presents in tabular form a portion of the data presented graphically in Figure 4.13.

A graphical comparison of the kinematic viscosity for R-236fa/Castrol SW-68 and R-236fa/Mobil Arctic-46 mixtures at 0 to 40 mass percent refrigerant is given in Figure 4.14. In addition to this figure. Table 4.15 compares the kinematic viscosity for the two lubricants with the same refrigerant at five different refrigerant

concentrations: 0, 10, 20, 30, and 40%. The kinematic viscosity of the R-236fa/SW-68 mixture is higher than R-236fa/Arctic-46 mixture for a given refrigerant concentrations. Table 4.15 presents in tabular form a portion of the data presented graphically in Figure 4.14.

Additionally, Figure 4.15. compares the density results for R-236fa/Casrtol SW-68 mixture and R-236fa/Mobil Arctic-46 mixture from 0 to 40 mass percent refrigerant. Table 4.16 lists a comparison of density for the two lubricants, each with R-236fa. at five different refrigerant concentrations: 0, 10, 20, 30, and 40% (by mass). The density of the R-236fa/SW-68 mixture is lower than R-236fa/Arctic-46 mixture at low refrigerant concentrations (0-10%), but at above 20% refrigerant concentration, the opposite trend is observed. Table 4.16 presents in tabular form a portion of the data presented graphically in Figure 4.15.

Table 4.13. Comparison of solubility for R-236fa/Castrol SW-68 and R-236fa/Mobil Arctic-46 mixtures at eight different temperatures

Ref. Con. mass fraction	Pressure (kPa)															
	Temperature															
	30°C		40°C		50°C		60°C		70°C		80°C		90°C		100°C	
	SW-68	Arctic 46	SW-68	Arctic-46	SW-68	Arctic-46	SW-68	Arctic-46	SW-68	Arctic-46	SW-68	Arctic-46	SW-68	Arctic-46	SW-68	Arctic-46
0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
10	140.7	145.5	206.9	188.3	264.9	237.5	314.5	293.3	355.7	355.5	388.6	424.2	413.2	499.3	429.4	580.9
20	253.7	250.4	362.4	324.2	463.4	410.9	556.9	510.5	642.7	623.1	720.9	748.6	791.5	887.1	854.5	1038.5
30	339.2	314.8	466.4	407.7	595.7	519.9	727.3	651.7	861.0	802.8	996.8	973.3	1134.9	1163.2	1275.1	1372.6
40	397.0	338.6	518.9	438.8	661.7	564.8	825.6	716.8	1010.5	894.6	1216.4	1098.3	1443.4	1327.8	1691.4	1583.3

Table 4.14. Comparison of dynamic viscosity for R-236fa/Castrol SW-68 and R-236fa/Mobil Arctic-46 mixtures at five different refrigerant concentrations

Temp. (°C)	Dynamic Viscosity (cP)									
	Refrigerant concentration (percentage by mass)									
	0%		10%		20%		30%		40%	
	SW-68	Arctic-46	SW-68	Arctic-46	SW-68	Arctic-46	SW-68	Arctic-46	SW-68	Arctic-46
30	134.48	83.35	65.60	36.82	33.14	18.12	17.34	9.93	9.40	6.06
40	79.00	49.22	41.23	23.66	22.07	12.46	12.12	7.19	6.83	4.54
50	48.19	30.44	26.81	15.78	15.14	8.81	8.68	5.30	5.05	3.44
60	30.54	19.73	18.04	10.93	10.70	6.41	6.37	3.99	3.81	2.63
70	20.10	13.39	12.56	7.86	7.79	4.80	4.79	3.06	2.93	2.03
80	13.74	9.52	9.05	5.86	5.84	3.70	3.69	2.39	2.29	1.58
90	9.75	7.09	6.74	4.54	4.51	2.93	2.92	1.90	1.82	1.25
100	7.19	5.54	5.20	3.65	3.59	2.39	2.36	1.55	1.48	0.99

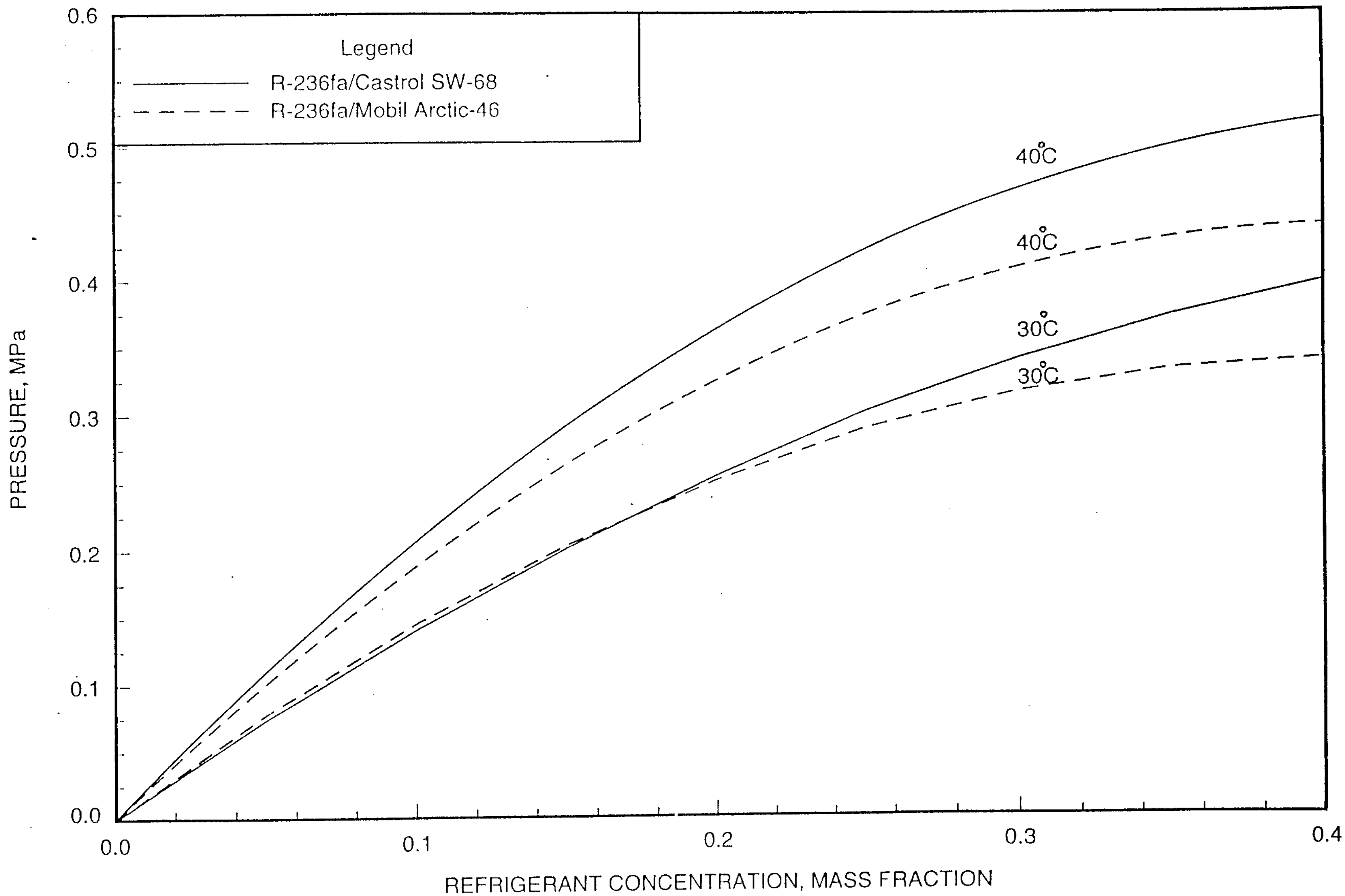

Figure 4.9 Solubility for R-236fa/Castrol SW-68 and R-236fa/Mobil Arctic-46 at 30°C and 40°C

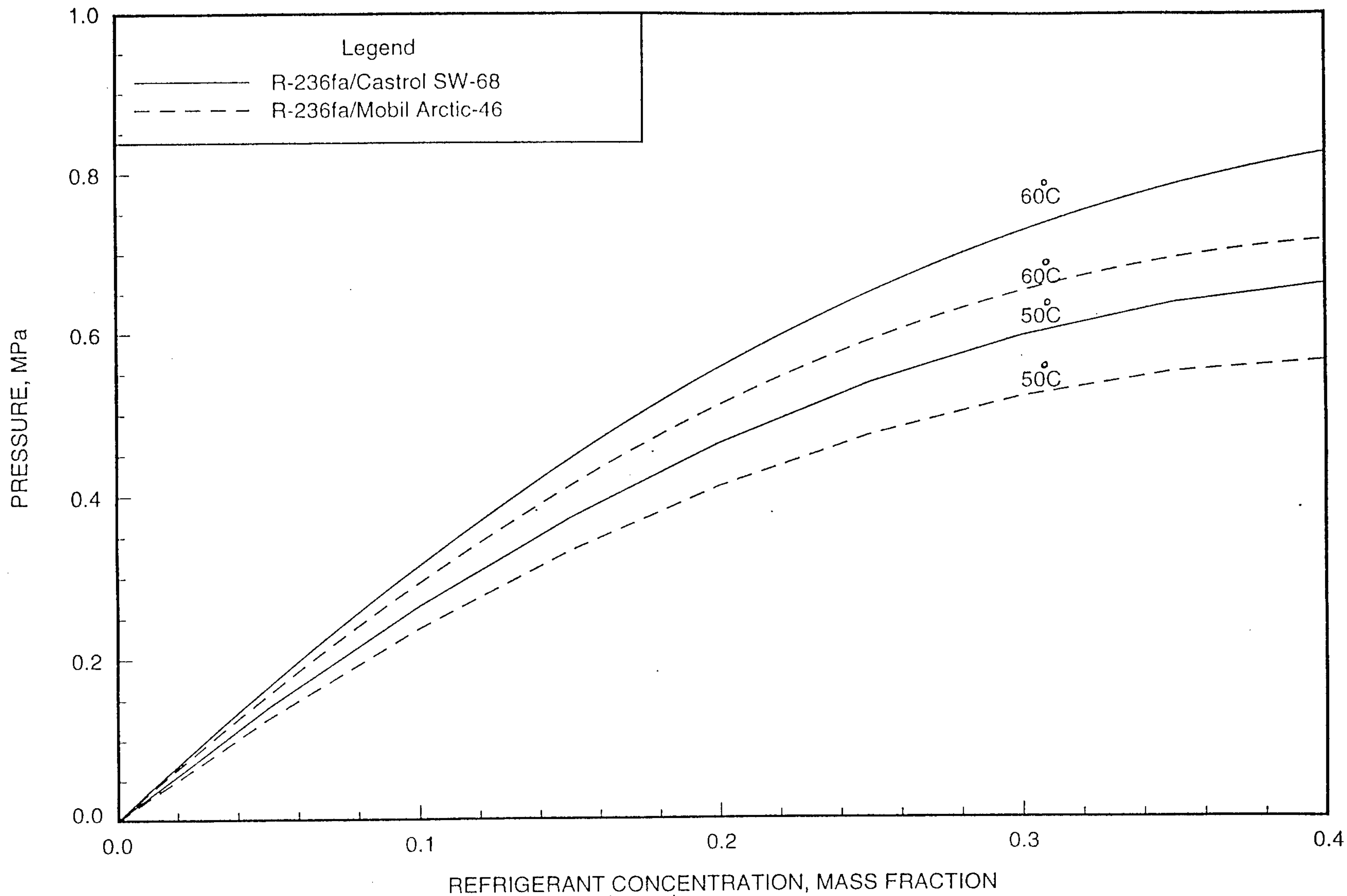

Figure 4.10. Solubility for R-236fa/Castrol SW-68 and R-236fa/Mobil Arctic-46 at 50°C and 60°C

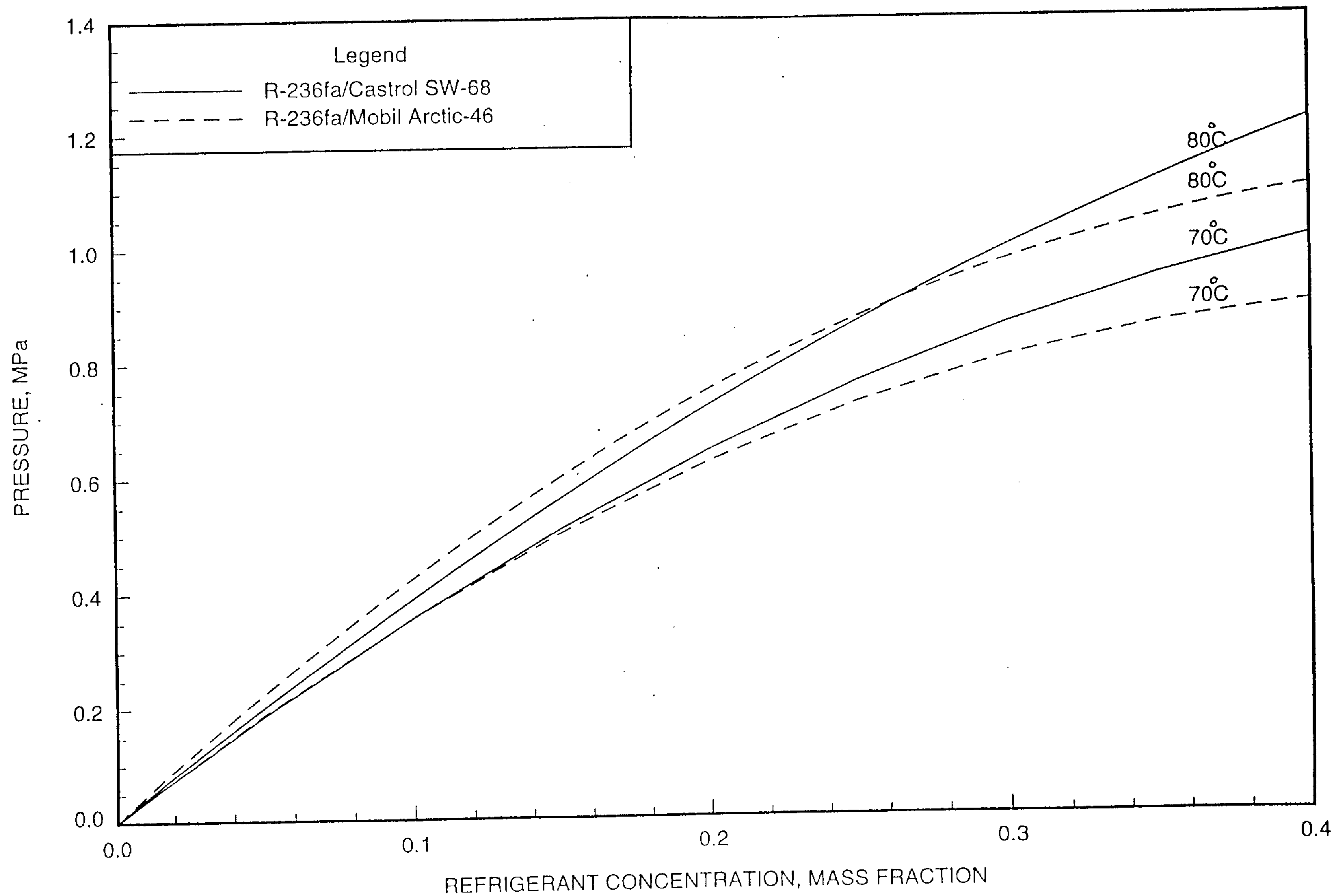

Figure 4.11. Solubility for R-236fa/Castrol SW-68 and R-236fa/Mobil Arctic-46 at 70°C and 80°C

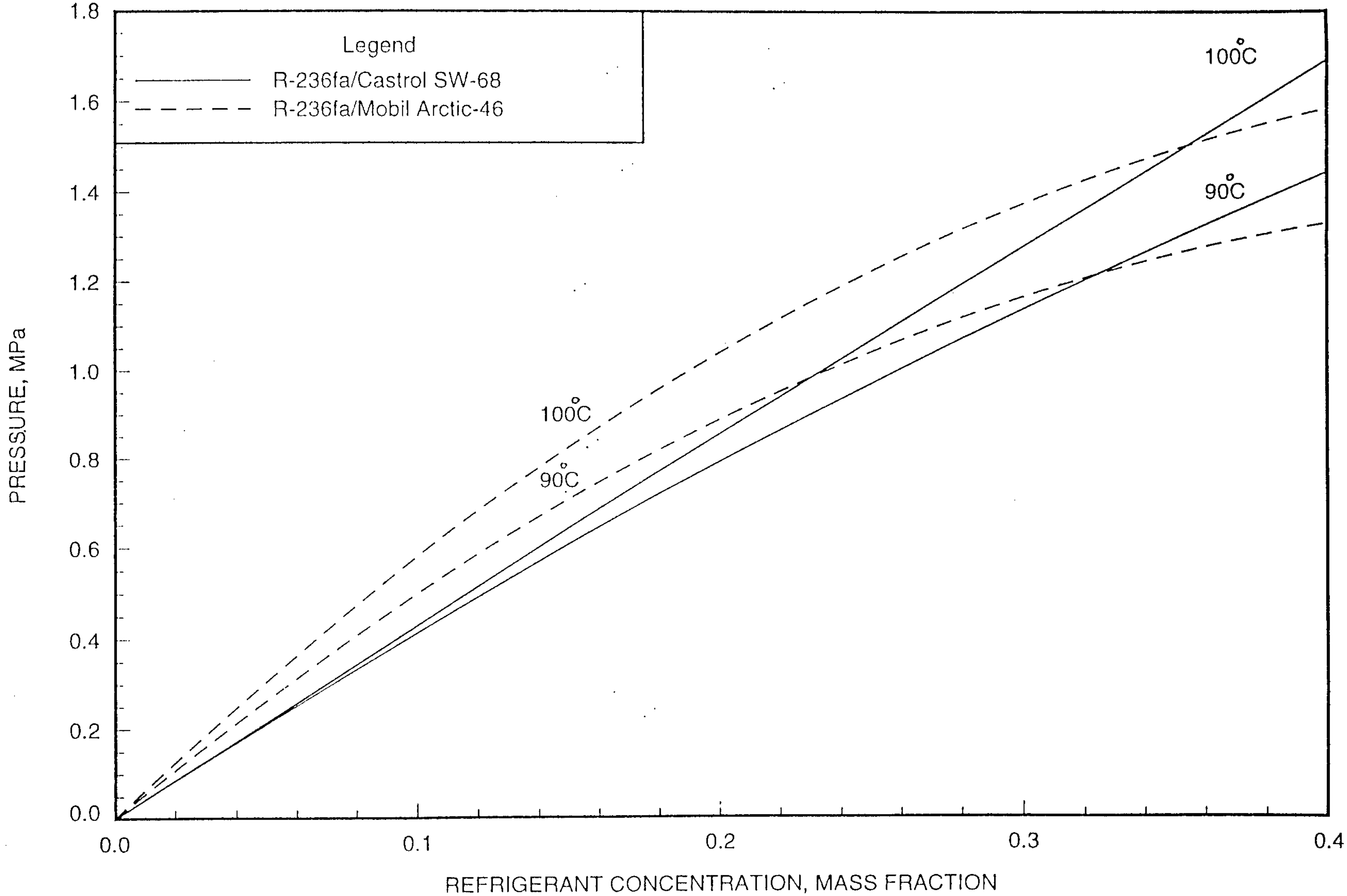

Figure 4.12. Solubility for R-236fa/Castrol SW-68 and R-236fa/Mobil Arctic-46 at 90°C and 100°C

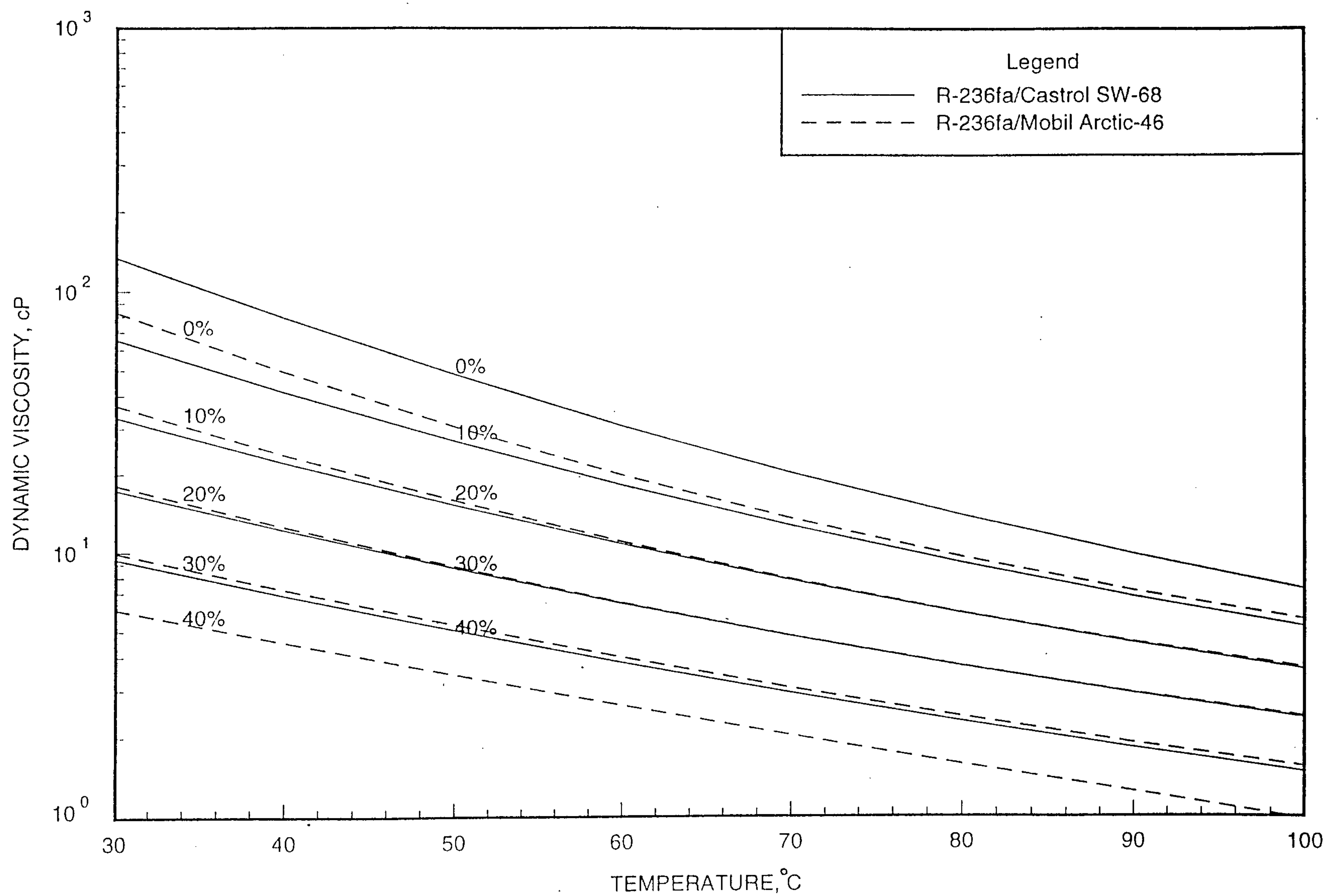

Figure 4.13. Dynamic viscosity for R-236fa/Castrol SW-68 and R-236fa/Mobil Arctic-46

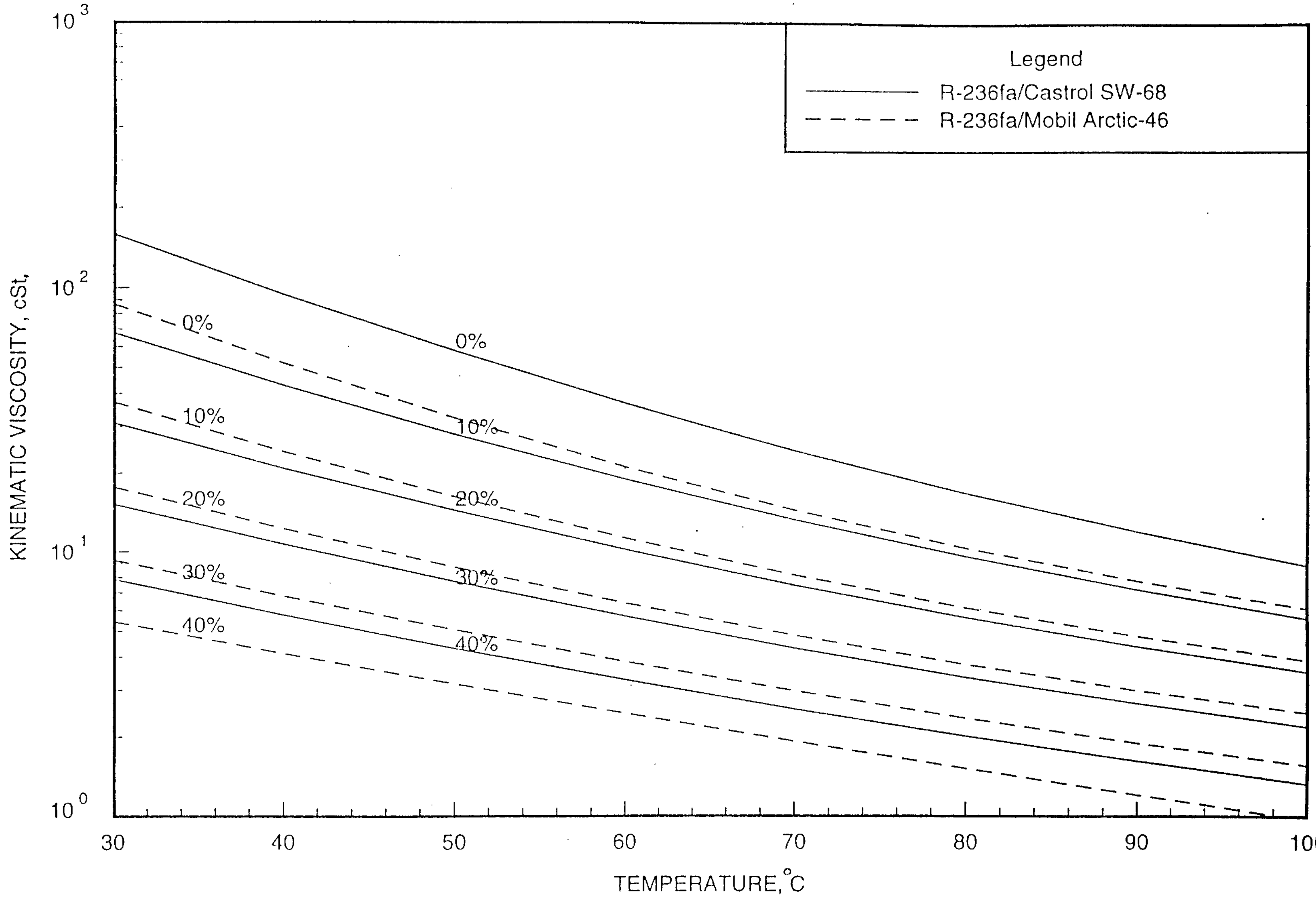

Figure 4.14. Kinematic viscosity for R-236fa/Castrol SW-68 and R-236fa/Mobil Arctic-46

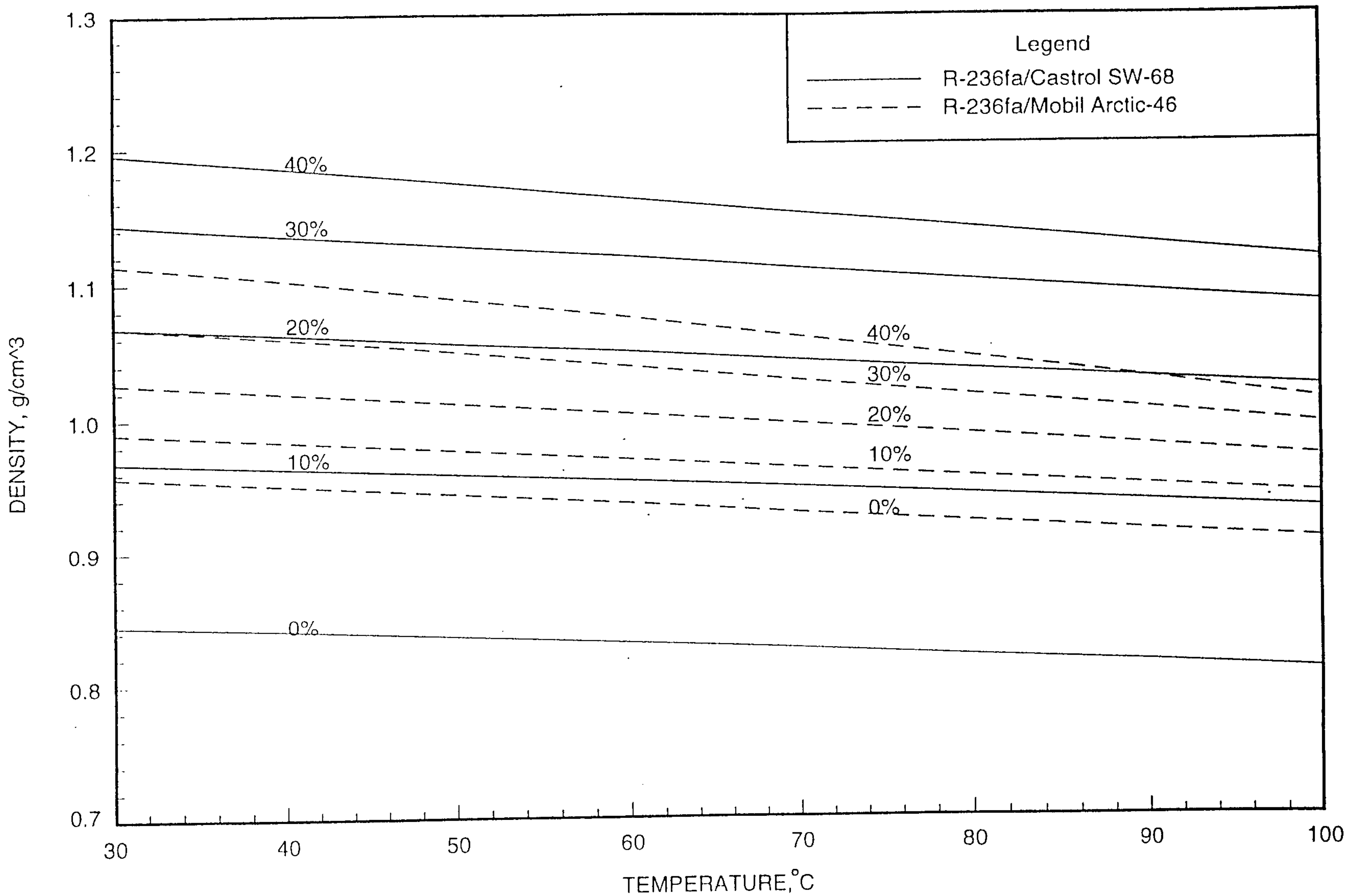

Figure 4.15. Density for R-236fa/Castrol SW-68 and R-236fa/Mobil Arctic-46

Table 4.15. Comparison of kinematic viscosity for R-236fa/Castrol SW-68 and R-236fa/Mobil Arctic-46 mixtures at five different refrigerant concentrations

Kinematic Viscosity (cSt)										
Temp. (°C)	Refrigerant concentration (percentage by mass)									
	0 %		10 %		20 %		30 %		40 %	
	SW-68	Arctic-46	SW-68	Arctic-46	SW-68	Arctic-46	SW-68	Arctic-46	SW-68	Arctic-46
30	159.11	87.05	67.75	37.20	31.04	17.65	15.16	9.30	7.86	5.44
40	93.88	51.80	42.80	24.07	20.79	12.23	10.68	6.79	5.76	4.12
50	57.67	32.29	27.98	16.17	14.35	8.72	7.70	5.06	4.30	3.16
60	36.76	21.09	18.93	11.28	10.20	6.39	5.70	3.84	3.28	2.45
70	24.34	14.43	13.26	8.17	7.47	4.83	4.32	2.98	2.54	1.92
80	16.74	10.34	9.61	6.14	5.64	3.75	3.35	2.35	2.01	1.52
90	11.96	7.76	7.20	4.79	4.38	2.99	2.67	1.89	1.62	1.21
100	8.88	6.11	5.59	3.88	3.51	2.46	2.18	1.56	1.33	0.98

Table 4.16. Comparison of density for R-236fa/Castrol SW-68 and R-236fa/Mobil Arctic-46 mixtures at five different refrigerant concentrations

Density (g/cm^3)										
Temp. (°C)	Refrigerant concentration (percentage by mass)									
	0%		10%		20%		30%		40%	
	SW-68	Arctic-46	SW-68	Arctic-46	SW-68	Arctic-46	SW-68	Arctic-46	SW-68	Arctic-46
30	0.845	0.957	0.968	0.990	1.068	1.027	1.144	1.068	1.196	1.114
40	0.841	0.950	0.963	0.983	1.062	1.019	1.135	1.059	1.185	1.102
50	0.836	0.943	0.958	0.976	1.055	1.011	1.127	1.049	1.174	1.088
60	0.831	0.936	0.953	0.969	1.049	1.003	1.119	1.038	1.162	1.074
70	0.826	0.928	0.947	0.962	1.042	0.995	1.110	1.027	1.151	1.059
80	0.820	0.921	0.942	0.955	1.035	0.987	1.101	1.016	1.140	1.044
90	0.815	0.914	0.936	0.948	1.028	0.978	1.092	1.005	1.128	1.028
100	0.809	0.907	0.930	0.941	1.021	0.969	1.083	0.993	1.116	1.011

4-4. SUMMARY

Miscibility data have been obtained and compared for mixtures of refrigerant R-236fa and two lubricants, which are designated as Castrol SW-68 and Mobil Arctic-46. Miscibility data have been observed from 25 to 85% refrigerant concentration (i.e., mass fraction of refrigerant) for the temperature range of -40 to +90°C (-40 to 194°F). The two refrigerant/lubricant pairs were found to be completely miscible over the temperature and concentration ranges tested.

Property data, such as solubility, viscosity, and density, were also measured and compared for temperatures as high as 100°C (212°F) and for pressures up to 3.5 MPa (500 psia). This research shows that for

both refrigerant/lubricant mixtures the solubility, viscosity, and density each is a function of temperature and concentration. Specifically, for both the R-236fa/Castrol SW-68 and R-236fa/Mobil Arctic-46 mixtures (1) the solubility increases with increasing temperature and with increasing refrigerant concentration (i.e., mass fraction of refrigerant), (2) the viscosity decreases with increasing temperature and with increasing refrigerant concentration, and (3) the density decreases with increasing temperature but increases with increasing refrigerant concentration.

The results are also presented as solubility, dynamic viscosity, kinematic viscosity, and density charts where the properties are plotted as a function of temperature and refrigerant concentration. Empirical correlating equations developed from these data allow convenient interpolation of the data at specific property conditions.

To better observe the solubility comparison, the compared plots and tabulated data are presented over narrow temperature ranges of 30 to 40°C, 50 to 60°C, 70 to 80°C, and 90 to 100°C, respectively. The pressure of the R-236fa/SW-68 mixture is higher for the temperatures from 30 to 70° C and for a given refrigerant concentration than the pressure of the corresponding R-236fa/Arctic-46 mixture, but at above 80° C temperature, the opposite trend is observed. A graphical comparison of the dynamic viscosity, kinematic viscosity, and density for R-236fa/Castrol SW-68 and R-236fa/Mobil Arctic-46 mixtures at 0 to 40 mass percent refrigerant is also presented along with tabulated data. The dynamic viscosity of the R-236fa/SW-68 mixture is higher than R-236fa/Arctic-46 mixture for a given refrigerant concentrations. The kinematic viscosity of the R-236fa/SW-68 mixture is higher than R-236fa/Arctic-46 mixture for a given refrigerant concentrations. The density of the R-236fa/SW-68 mixture is lower than R-236fa/Arctic-46 mixture at low refrigerant concentrations (0-10%), but at above 20% refrigerant concentration, the opposite trend is observed.

CHAPTER 5

COMPARISON OF THREE DIFFERENT REFRIGERANT/LUBRICANT MIXTURES

This chapter presents a comparison of miscibility, solubility, viscosity, and density for three different refrigerant/lubricant pairs, namely R-236ea/Castrol-68, R-236fa/Castrol-68, and R-114/naphthenic mineral oil. The refrigerant/lubricant mixtures are compared at various refrigerant concentrations and temperatures. The purpose of these comparison is to determine whether the non-CFC refrigerant reported in this study (i.e., R-236fa) may be a satisfactory replacement for R-114.

The results of R-236fa with Castrol SW-68 mixture study were compared to R-236ea and R-114 mixed with the Castrol SW-68 and naphthenic mineral oil, respectively.

Similar property results for R-236ea and Castrol SW-68 mixtures along with results for R-114 and naphthenic mineral oil mixtures were reported by Zoz and Pate(1996).

5-1. COMPARISON OF R-236fa/CASTROL SW-68 AND R-236ea/CASTROL SW-68 MIXTURES

5-1-1. MISCIBILITY

The results of miscibility tests for R-236fa/CASTROL SW-68 and R-236ea/CASTROL SW-68 mixtures showed that both refrigerant/lubricant mixtures were completely miscible with this lubricant over the temperature and refrigerant concentration ranges tested which were -40 to 90°C (-40 to 194°F) and 25 to 85% (by mass), respectively.

5-1-2. SOLUBILITY, VISCOSITY, AND DENSITY

To better observe the comparison, the compared plots are presented over narrow temperature ranges. Specifically, Figures 5.1 through 5.4 permit comparing the solubility results for R-236fa/Castrol SW-68 and R-236ea/Castrol SW-68 mixtures at temperatures ranges of 30 to 40°C, 50 to 60°C, 70 to 80°C, and 90 to 100°C, respectively. In addition to these figures, Table 5.1 gives solubility of each refrigerant with Castrol SW-68 lubricant at eight different temperatures, which are 30° C, 40° C, 50° C, 60° C, 70° C, 80° C, 90° C, and 100°C. The pressure of the R-236fa/SW-68 mixture is higher for a given temperature and refrigerant concentration than

the pressure of the corresponding R-236ea/SW-68 mixture. Table 5.1 tabulates a portion of the data presented graphically in Figures 5.1 through 5.4.

A graphical comparison of the dynamic viscosity for R-236fa/Castrol SW-68 and R-236ea/Castrol SW-68 mixtures at 0 to 40 mass percent refrigerant is given in Figure 5.5. In addition to this figure. Table 5.2 compares the dynamic viscosity for the two refrigerants with the same lubricant at five different concentrations, which are 0. 10, 20. 30. and 40% refrigerant concentration. respectively. The dynamic viscosity of the R-236fa/SW-68 mixture is higher than R-236ea/SW-68 mixture at low refrigerant concentrations (10-30%). but at above 40% refrigerant concentration. the opposite trend is observed. Table 5.2 presents in tabular form a portion of the data presented graphically in Figure 5.5.

A graphical comparison of the kinematic viscosity for R-236fa/Castrol SW-68 and R-236ea/Castrol SW-68 mixtures at 0 to 40 mass percent refrigerant is given in Figure 5.6. In addition to this figure, Table 5.3 compares the kinematic viscosity for the two refrigerants with the same lubricant at five different refrigerant concentrations: 0. 10. 20. 30. and 40%. The kinematic viscosity of the R-236fa/SW-68 mixture is higher than R-236ea/SW-68 mixture at low refrigerant concentrations (10-20%). but at above 30% refrigerant concentration. the opposite trend is observed. Table 5.3 presents in tabular form a portion of the data presented graphically in Figure 5.6.

Additionally. Figure 5.7. compares the density results for R-236fa/Casrtol SW-68 mixture and R-236ea/Castrol SW-68 mixture from 0 to 40 mass percent refrigerant. Table 5.4 lists a comparison of density for the two refrigerants. each with Castrol SW-68, at five different refrigerant concentrations: 0. 10. 20. 30. and 40% (by mass). The density of the R-236fa/SW-68 mixture is lower than R-236ea/SW-68 mixture at low refrigerant concentrations (10%), but at above 20% refrigerant concentration. the opposite trend is observed. Table 5.4 presents in tabular form a portion of the data presented graphically in Figure 5.7.

Table 5.1. Comparison of solubility for R-236fa/Castrol SW-68 and R-236ea/Castrol SW-68 mixtures at eight different temperatures

Pressure (kPa)																
Ref. Con.	Temperature															
mass	30°C		40°C		50°C		60°C		70°C		80°C		90°C		100°C	
fract.	fa	ea	fa	ea	fa	ea	fa	ea	fa	ea	fa	ea	fa	ea	fa	ea
0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
10	140 7	52.7	206.9	69.8	264.9	93 6	314.5	123.9	355 7	160.9	388.6	204 4	413.2	254.6	429 4	311 4
20	253.7	98 6	362.4	131.0	463 4	176.1	556 9	233.9	642.7	304.5	720.9	387.7	791.5	483.6	854 5	592.3
30	339 2	137.6	466.4	183 4	595.7	247 6	727.3	330.0	861.0	430 8	996 8	549.8	1134 9	687.1	1275.1	842 7
40	397 0	169.8	518.9	227.2	661 7	308 0	825 6	412.2	1010.5	539.8	1216 4	690 7	1443 4	865.0	1691.4	1062 6

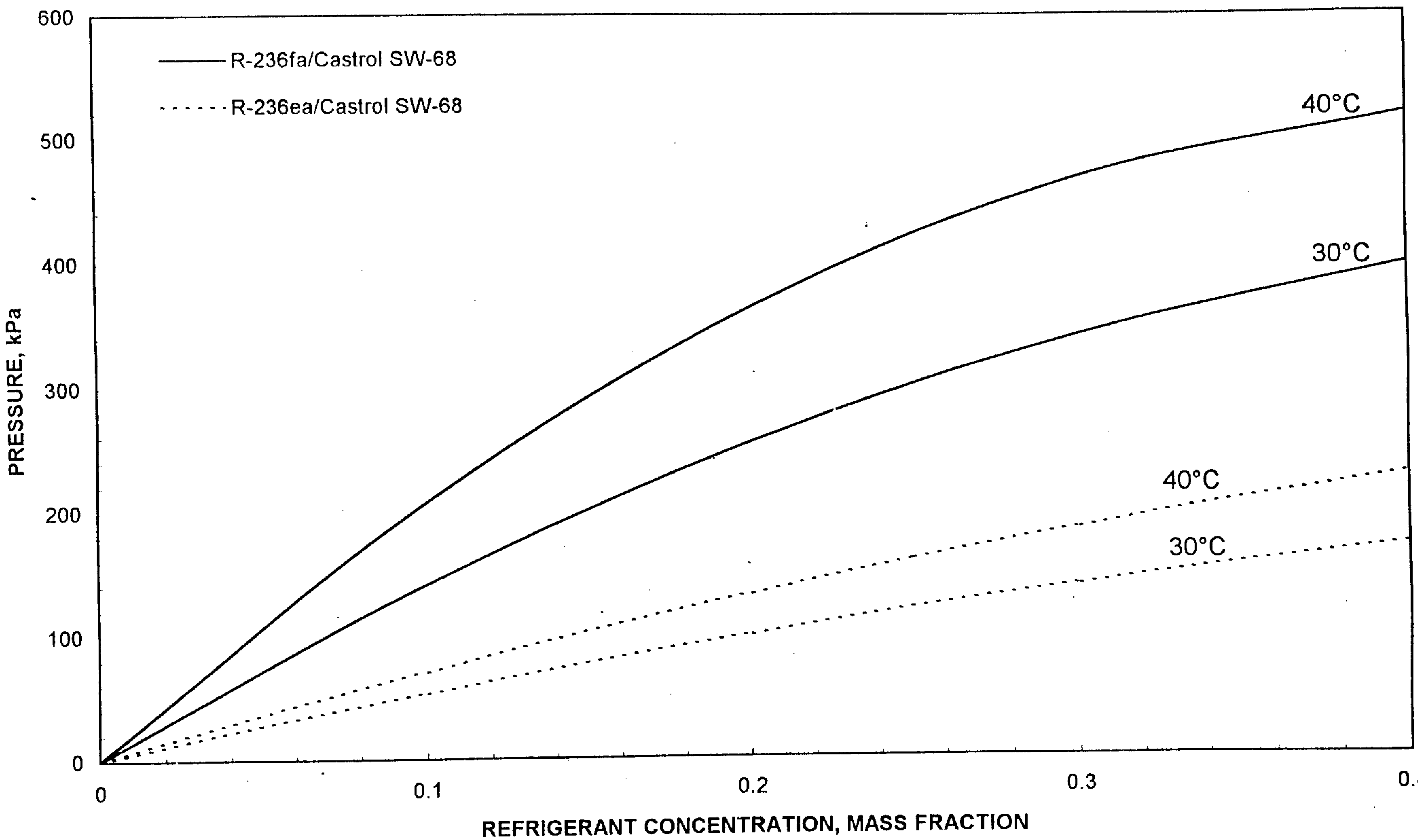

Figure 5.1. Solubility for R-236fa/Castrol SW-68 and R-236ea/Castrol SW-68 at 30°C and 40°C

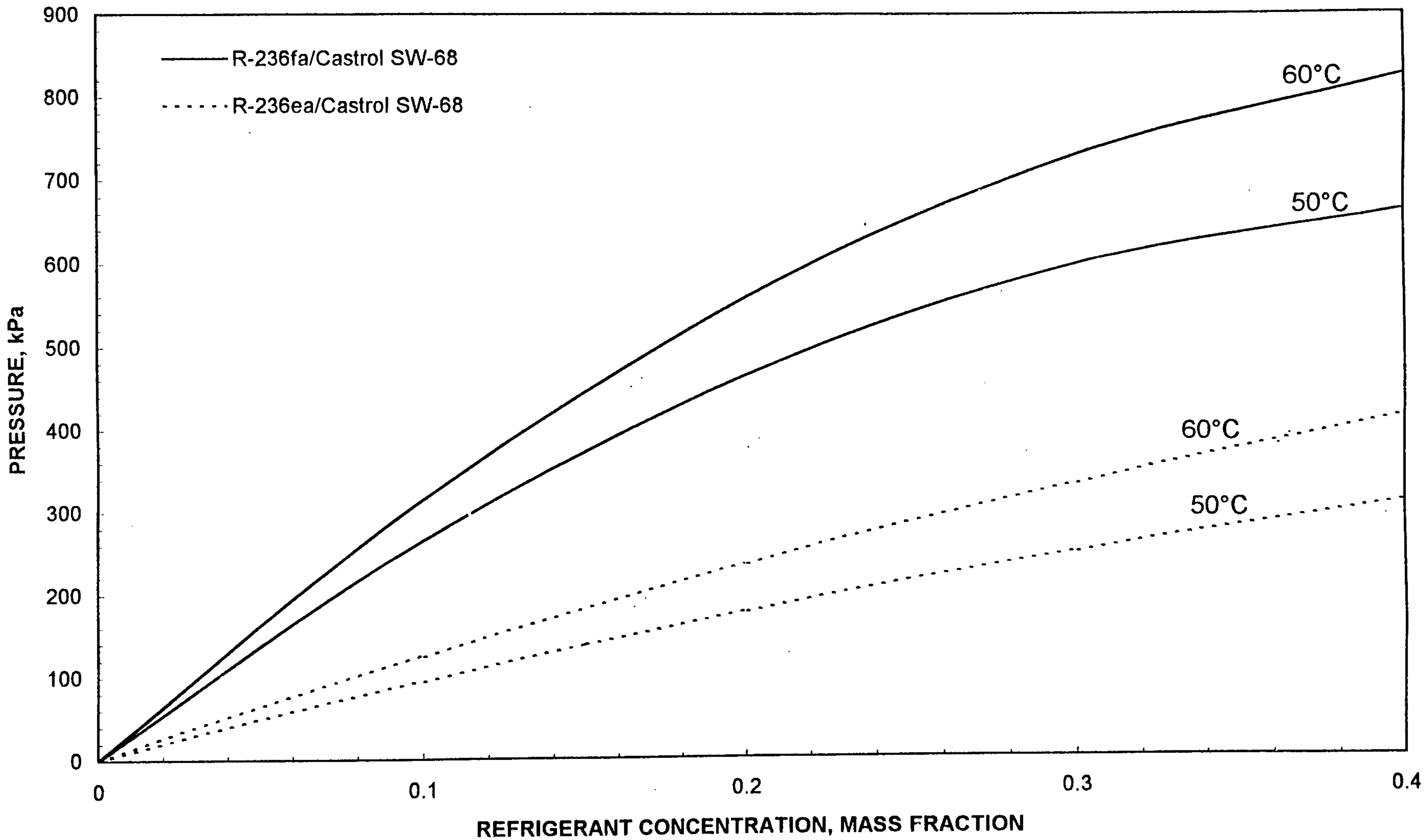

Figure 5.2. Solubility for R-236fa/Castrol SW-68 and R-236ea/Castrol SW-68 at 50°C and 60°C

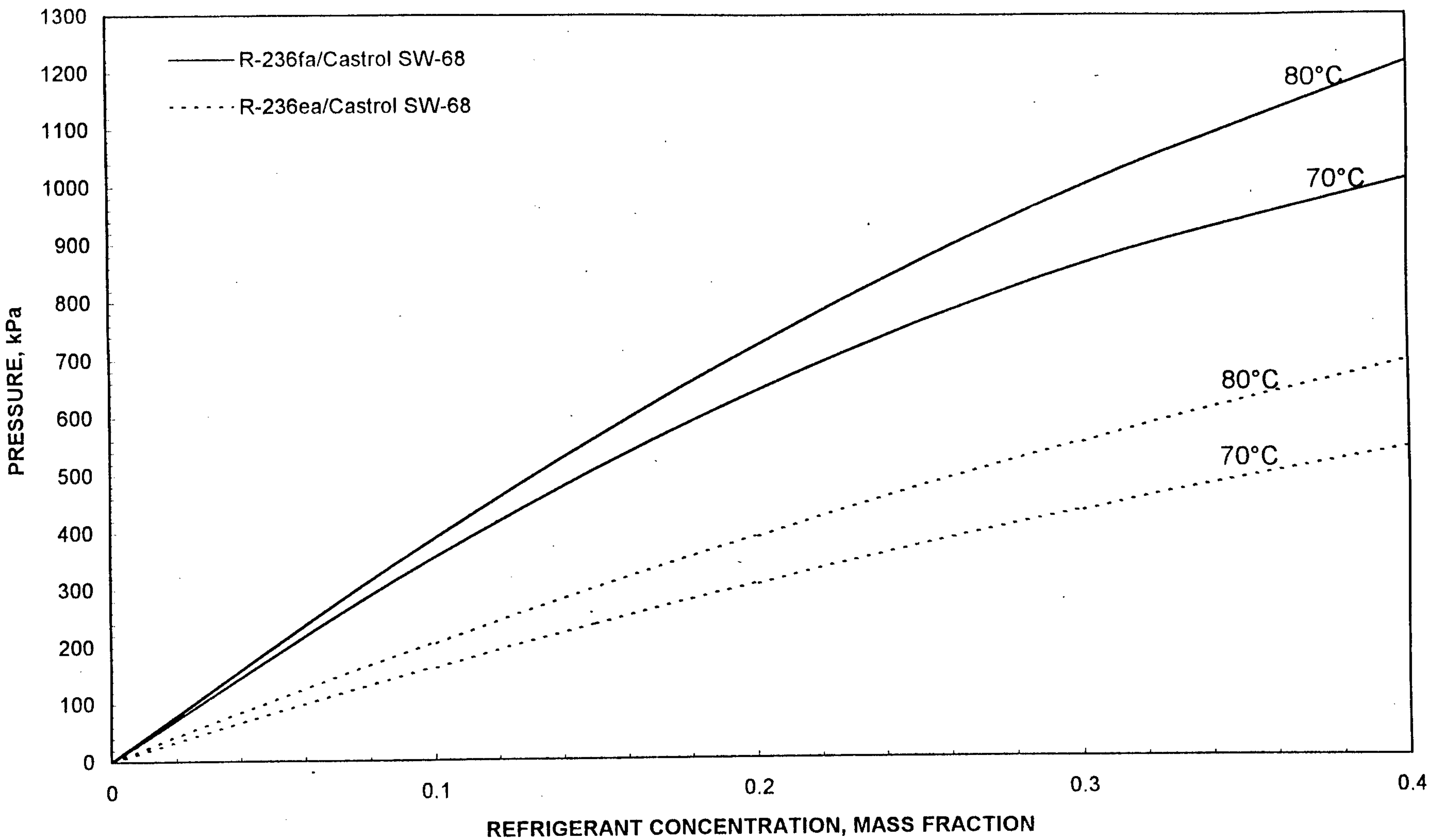

Figure 5.3. Solubility for R-236fa/Castrol SW-68 and R-236ea/Castrol SW-68 at 70°C and 80°C

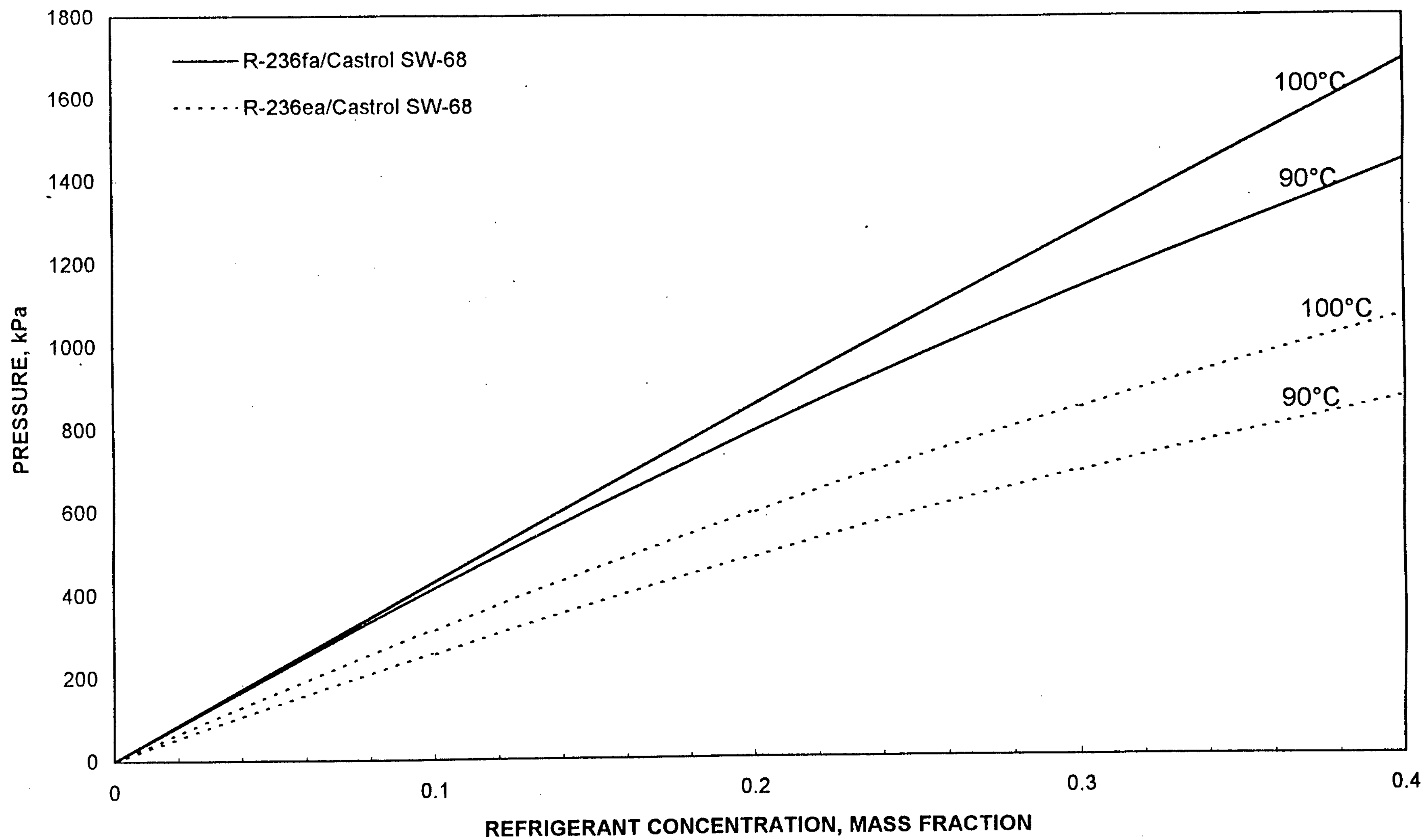

Figure 5.4. Solubility for R-236fa/Castrol SW-68 and R-236ea/Castrol SW-68 at 90°C and 100°C

Table 5.2. Comparison of dynamic viscosity for R-236fa/Castrol SW-68 and R-236ea/Castrol SW-68 mixtures at five different refrigerant concentrations

Temp. (°C)	Dynamic Viscosity (cP)									
	Refrigerant concentration (percentage by mass)									
	0%		10%		20%		30%		40%	
	R-236fa	R-236ea	R-236fa	R-236ea	R-236fa	R-236ea	R-236fa	R-236ea	R-236fa	R-236ea
30	134.48	104.84	65.60	57.18	33.14	31.39	17.34	17.36	9.40	9.66
40	79.00	63.07	41.23	36.01	22.07	20.71	12.12	11.99	6.83	7.00
50	48.19	39.62	26.81	23.55	15.14	14.11	8.68	8.52	5.05	5.18
60	30.54	25.99	18.04	16.00	10.70	9.93	6.37	6.21	3.81	3.92
70	20.10	17.80	12.56	11.29	7.79	7.22	4.79	4.66	2.93	3.03
80	13.74	12.73	9.05	8.27	5.84	5.42	3.69	3.59	2.29	2.40
90	9.75	9.51	6.74	6.29	4.51	4.21	2.92	2.84	1.82	1.94
100	7.19	7.41	5.20	4.97	3.59	3.37	2.36	2.31	1.48	1.60

Table 5.3. Comparison of kinematic viscosity for R-236fa/Castrol SW-68 and R-236ea/Castrol SW-68 mixtures at five different refrigerant concentrations

Temp. (°C)	Kinematic Viscosity (cSt)									
	Refrigerant concentration (percentage by mass)									
	0 %		10 %		20 %		30 %		40 %	
	R-236fa	R-236ea	R-236fa	R-236ea	R-236fa	R-236ea	R-236fa	R-236ea	R-236fa	R-236ea
30	159.11	108.23	67.75	57.06	31.04	30.26	15.16	16.14	7.86	8.66
40	93.88	65.57	42.80	36.20	20.79	20.11	10.68	11.25	5.76	6.33
50	57.67	41.49	27.98	23.85	14.35	13.81	7.70	8.05	4.30	4.73
60	36.76	27.41	18.93	16.32	10.20	9.80	5.70	5.93	3.28	3.62
70	24.34	18.91	13.26	11.60	7.47	7.18	4.32	4.49	2.54	2.83
80	16.74	13.62	9.61	8.57	5.64	5.44	3.35	3.49	2.01	2.26
90	11.96	10.25	7.20	6.57	4.38	4.26	2.67	2.79	1.62	1.84
100	8.88	8.05	5.59	5.23	3.51	3.44	2.18	2.29	1.33	1.54

Table 5.4. Comparison of density for R-236fa/Castrol SW-68 and R-236ea/Castrol SW-68 mixtures at five different refrigerant concentrations

Temp. (°C)	Density (g/cm^3)									
	Refrigerant concentration (percentage by mass)									
	0%		10%		20%		30%		40%	
	R-236fa	R-236ea	R-236fa	R-236ea	R-236fa	R-236ea	R-236fa	R-236ea	R-236fa	R-236ea
30	0.845	0.969	0.968	1.002	1.068	1.038	1.144	1.076	1.196	1.116
40	0.841	0.962	0.963	0.995	1.062	1.030	1.135	1.067	1.185	1.105
50	0.836	0.955	0.958	0.987	1.055	1.021	1.127	1.057	1.174	1.095
60	0.831	0.948	0.953	0.980	1.049	1.013	1.119	1.048	1.162	1.084
70	0.826	0.941	0.947	0.973	1.042	1.005	1.110	1.038	1.151	1.073
80	0.820	0.934	0.942	0.965	1.035	0.997	1.101	1.029	1.140	1.062
90	0.815	0.928	0.936	0.958	1.028	0.988	1.092	1.019	1.128	1.050
100	0.809	0.921	0.930	0.950	1.021	0.980	1.083	1.009	1.116	1.038

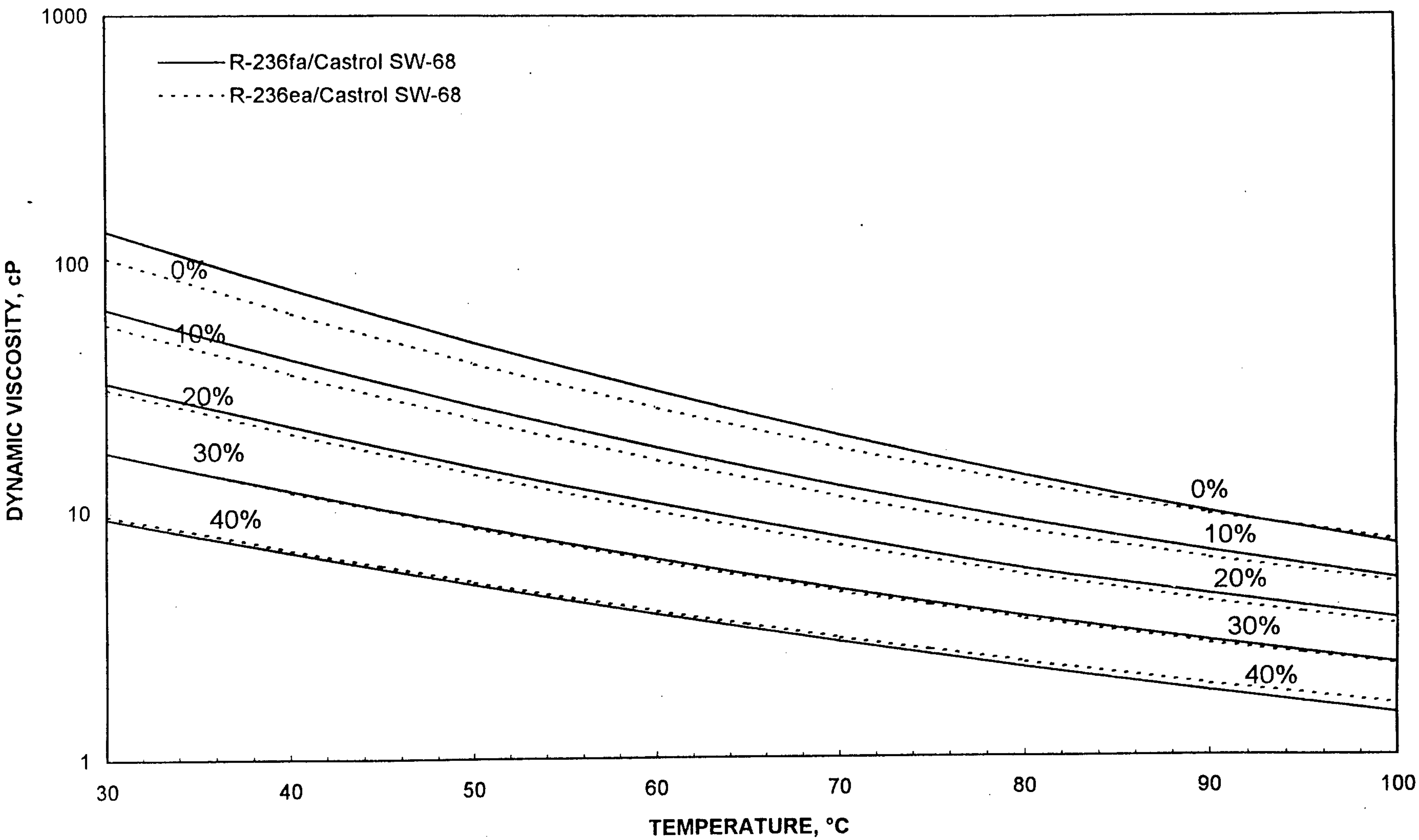

Figure 5.5. Dynamic viscosity for R-236fa/Castrol SW-68 and R-236ea/Castrol SW-68

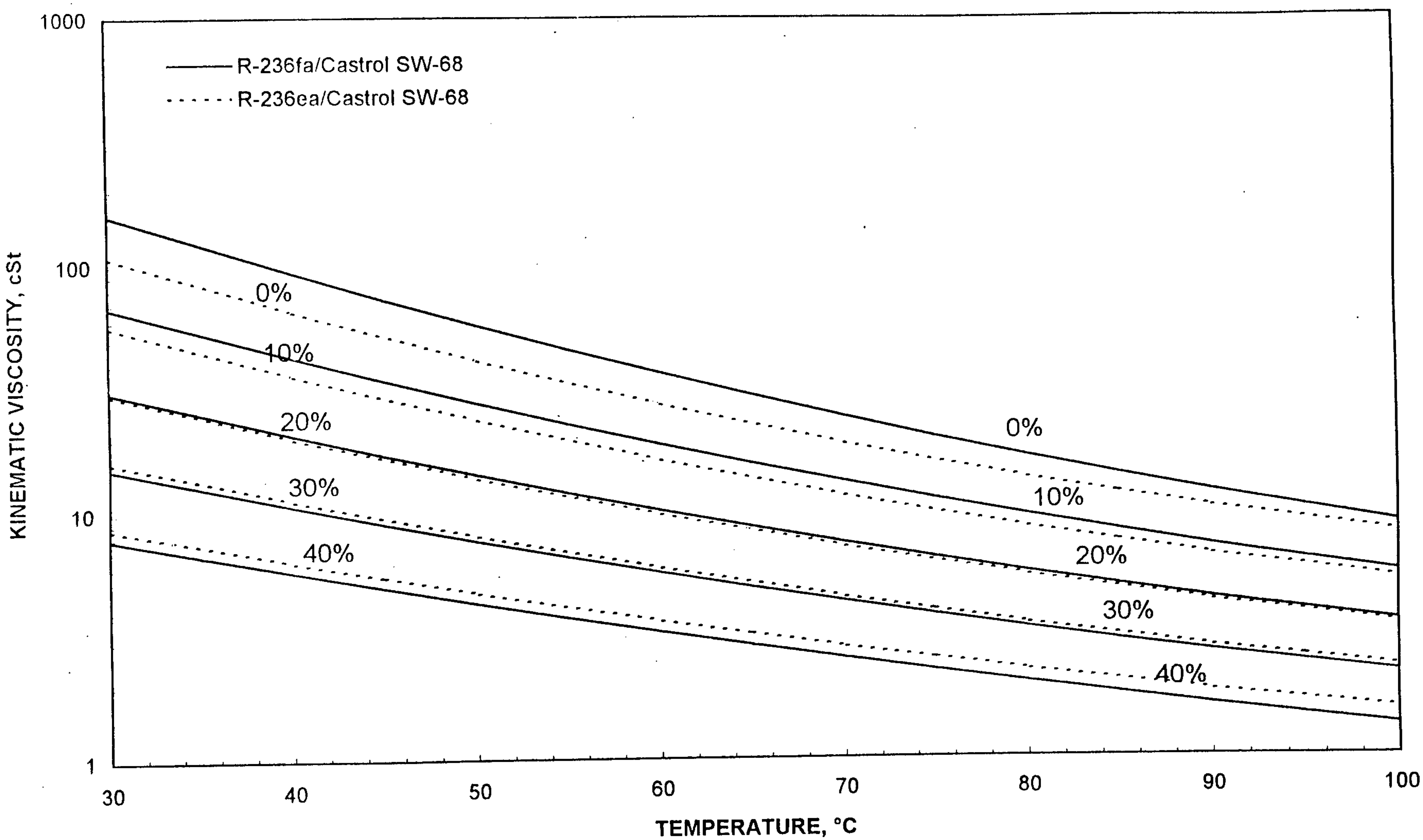

Figure 5.6. Kinematic viscosity for R-236fa/Castrol SW-68 and R-236ea/Castrol SW-68

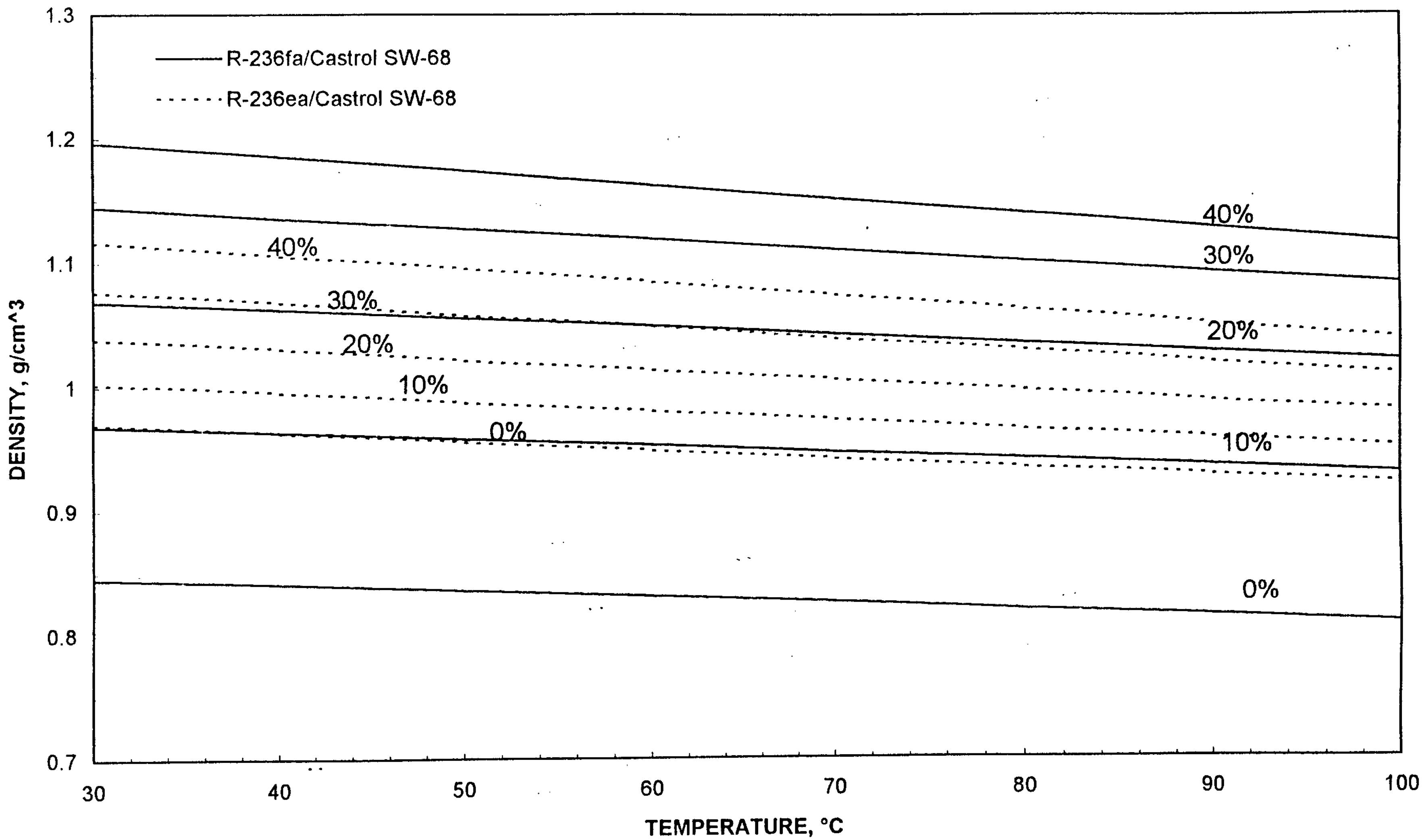

Figure 5.7. Density for R-236fa/Castrol SW-68 and R-236ea/Castrol SW-68

5-2. COMPARISON OF R-236fa/CASTROL SW-68 AND R-114/NAPHTHENIC MINERAL OIL MIXTURES

5-2-1. MISCIBILITY

The results of miscibility tests for R-236fa/Castrol SW-68 mixture and R-114/naphthenic mineral oil mixture showed that both refrigerant/lubricant mixtures were completely miscible over the temperature and refrigerant concentration ranges tested which were -40 to 90°C (-40 to 194°F) and 25 to 85% (by mass), respectively.

5-2-2. SOLUBILITY, VISCOSITY, AND DENSITY

To better show the comparison of the two refrigerant/lubricant mixtures, the comparison plots are presented over narrow temperature ranges. Specifically, Figures 5.8 through 5.11 present the solubility results for R-236fa/Castrol SW-68 and R-114/naphthenic mineral oil mixtures at temperatures of 30 to 40°C, 50 to 60°C, 70 to 80°C. and 90 to 100°C, respectively. In addition to these figures, Table 5.5 gives the pressure of the R-236fa/Castrol SW-68 and R-114/naphthenic mineral oil mixtures at eight different temperatures: 30° C, 40° C, 50 ° C, 60° C. 70° C, 80° C, 90° C, and 100°C. The pressure of the R-236fa/SW-68 mixture is higher for a given temperature and refrigerant concentration than the pressure of the R-114/naphthenic mineral oil mixture. Table 5.5 tabulates a portion of the data presented graphically in Figures 5.8 through 5.11.

A graphical comparison of the dynamic viscosity for R-236fa/Castrol SW-68 and R-114/naphthenic mineral oil mixtures at 0 to 40 mass percent refrigerant is given in Figure 5.12. In addition to this figure. Table 5.6 compares dynamic viscosity between R-236fa with Castrol SW-68 and R-114 with naphthenic mineral oil at five different refrigerant concentrations: 0, 10, 20, 30, and 40% (by mass). The dynamic viscosity of R-236fa/SW-68 mixture is higher for a given temperature and refrigerant concentration than the dynamic viscosity of the R-114/naphthenic mineral oil mixture. Table 5.6 tabulates a portion of the data presented graphically in Figure 5.12.

A graphical comparison of the kinematic viscosity for R-236fa/Castrol SW-68 and R-114/naphthenic mineral oil mixtures at 0 to 40 mass percent refrigerant is given in Figure 5.13. In addition to this figure, Table 5.7 compares kinematic viscosity between R-236fa with Castrol SW-68 and R-114 with naphthenic mineral oil at five different refrigerant concentrations: 0, 10, 20, 30. and 40% (by mass). The kinematic viscosity of the R-236fa/SW-68 mixture is higher for a given temperature and refrigerant concentration than the kinematic viscosity of the R-114/naphthenic mineral oil mixture. Table 5.7 tabulates a portion of the data presented graphically in Figure 5.13.

Additionally, Figure 5.14. compares the density results for R-236fa/Casrtol SW-68 and R-114/naphthenic mineral oil mixtures at 0 to 40 mass percent refrigerant. Table 5.8 lists a comparison of density between R-236fa

with Castrol SW-68 and R-114 with naphthenic mineral oil mixtures at five different concentration: 0, 10, 20, 30, and 40% (by mass). The density of the R-236fa/SW-68 mixture is higher than R-114/naphthenic mineral oil mixture at high refrigerant concentrations (10 to 40%), but for the density of pure lubricant. Castrol SW-68 has a lower density than naphthenic mineral oil. Table 5.8 tabulates a portion of the data presented graphically in Figure 5.14.

Table 5.5. Comparison of solubility for R-236fa/SW-68 and R-114/naphthenic mineral oil mixtures at eight different temperatures

Pressure (kPa)																
Ref.	Temperature															
Con	30°C		40°C		50°C		60°C		70°C		80°C		90°C		100°C	
	fa	R-114	fa	R-114	fa	R-114	fa	R-114	fa	R-114	fa	R-114	fa	R-114	fa	R-114
0%	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
10%	140.7	105.7	206.9	133.0	264.9	164.8	314.5	201.0	355.7	241.7	388.6	286.8	413.2	336.4	429.4	390.4
20%	253.7	186.9	362.4	235.1	463.4	292.2	556.9	358.2	642.7	433.1	720.9	516.8	791.5	609.5	854.5	711.0
30%	339.2	243.5	466.4	306.1	595.7	382.1	727.3	471.4	861.0	574.0	996.8	690.0	1134.9	819.2	1275.1	961.9
40%	397.0	275.7	518.9	346.2	661.7	434.6	825.6	540.7	1010.5	664.6	1216.4	806.2	1443.4	965.7	1691.4	1142.9

Table 5.6. Comparison of dynamic viscosity for R-236fa/SW-68 and R-114/naphthenic mineral oil mixtures at five different refrigerant concentrations

Dynamic viscosity (cP)										
Temp.	Refrigerant concentration (percentage by mass)									
(°C)	0%		10%		20%		30%		40%	
	R-236fa	R-114	R-236fa	R-114	R-236fa	R-114	R-236fa	R-114	R-236fa	R-114
30	134.48	89.04	65.60	40.66	33.14	20.24	17.34	10.98	9.40	6.49
40	79.00	49.12	41.23	24.80	22.07	13.42	12.12	7.77	6.83	4.82
50	48.19	28.84	26.81	15.87	15.14	9.22	8.68	5.65	5.05	3.66
60	30.54	18.03	18.04	10.65	10.70	6.56	6.37	4.22	3.81	2.83
70	20.10	11.99	12.56	7.49	7.79	4.84	4.79	3.23	2.93	2.23
80	13.74	8.49	9.05	5.53	5.84	3.70	3.69	2.55	2.29	1.80
90	9.75	6.40	6.74	4.28	4.51	2.93	2.92	2.06	1.82	1.48
100	7.19	5.13	5.20	3.47	3.59	2.41	2.36	1.71	1.48	1.24

5-3. SUMMARY

Data collected for R-236fa/SW-68 in this study were compared with data for R-236ea/SW-68 and R-114/naphthenic mineral oil taken in a previous study. The miscibility tests showed that R-236fa/SW-68, R-

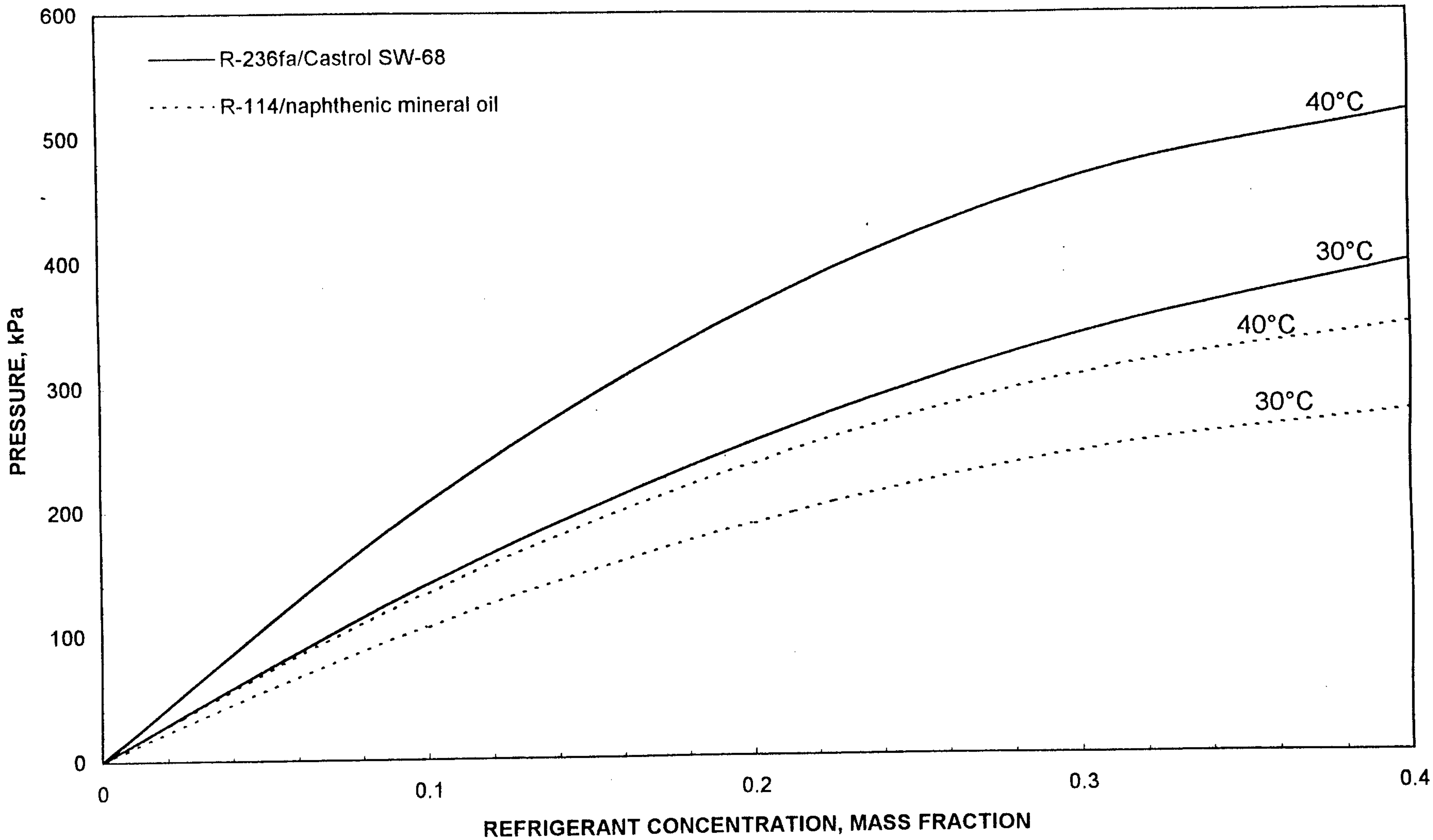

Figure 5.8. Solubility for R-236fa/Castrol SW-68 and R-114/naphthenic mineral oil at 30°C and 40°C

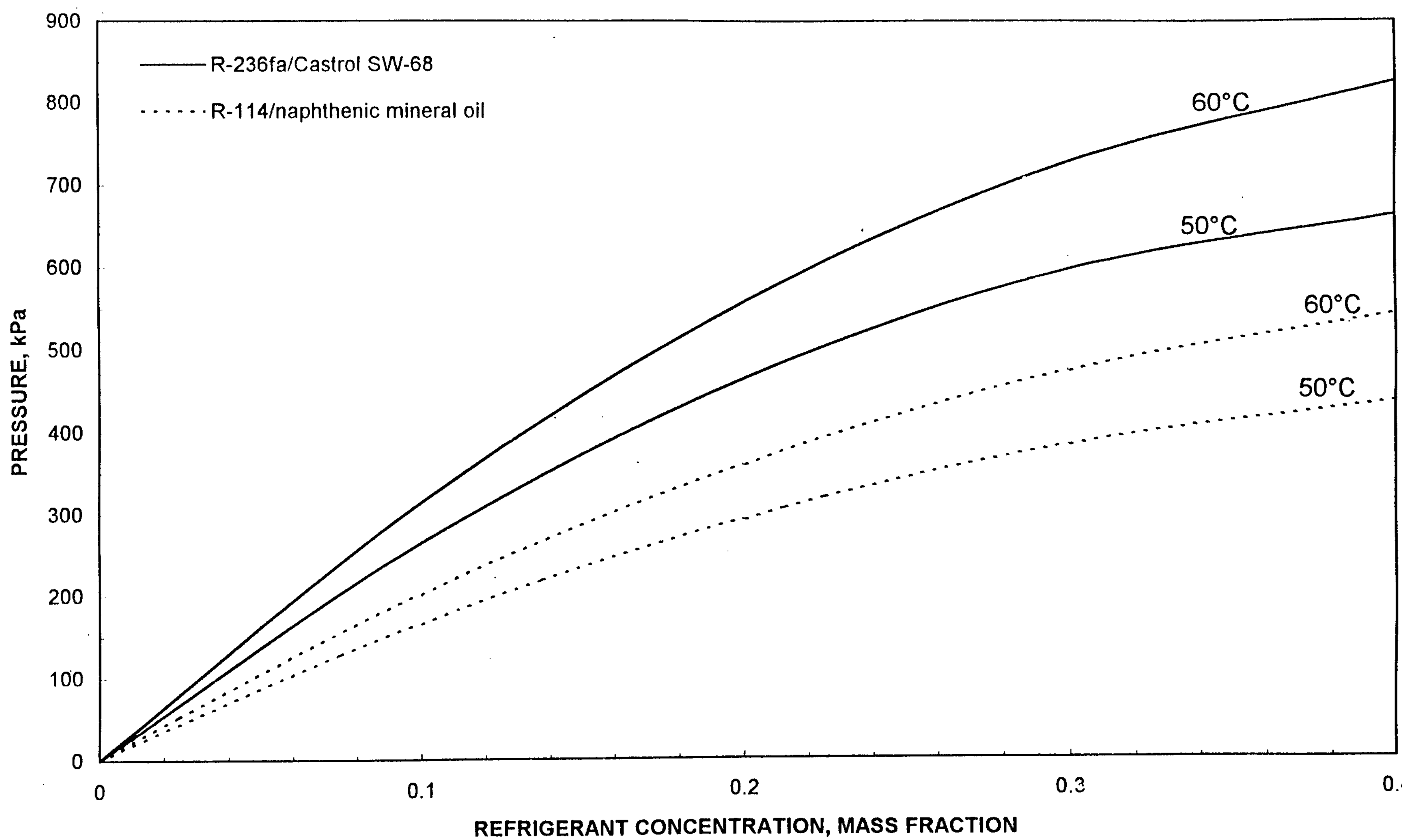

Figure 5.9. Solubility for R-236fa/Castrol SW-68 and R-114/naphthenic mineral oil at 50°C and 60°C

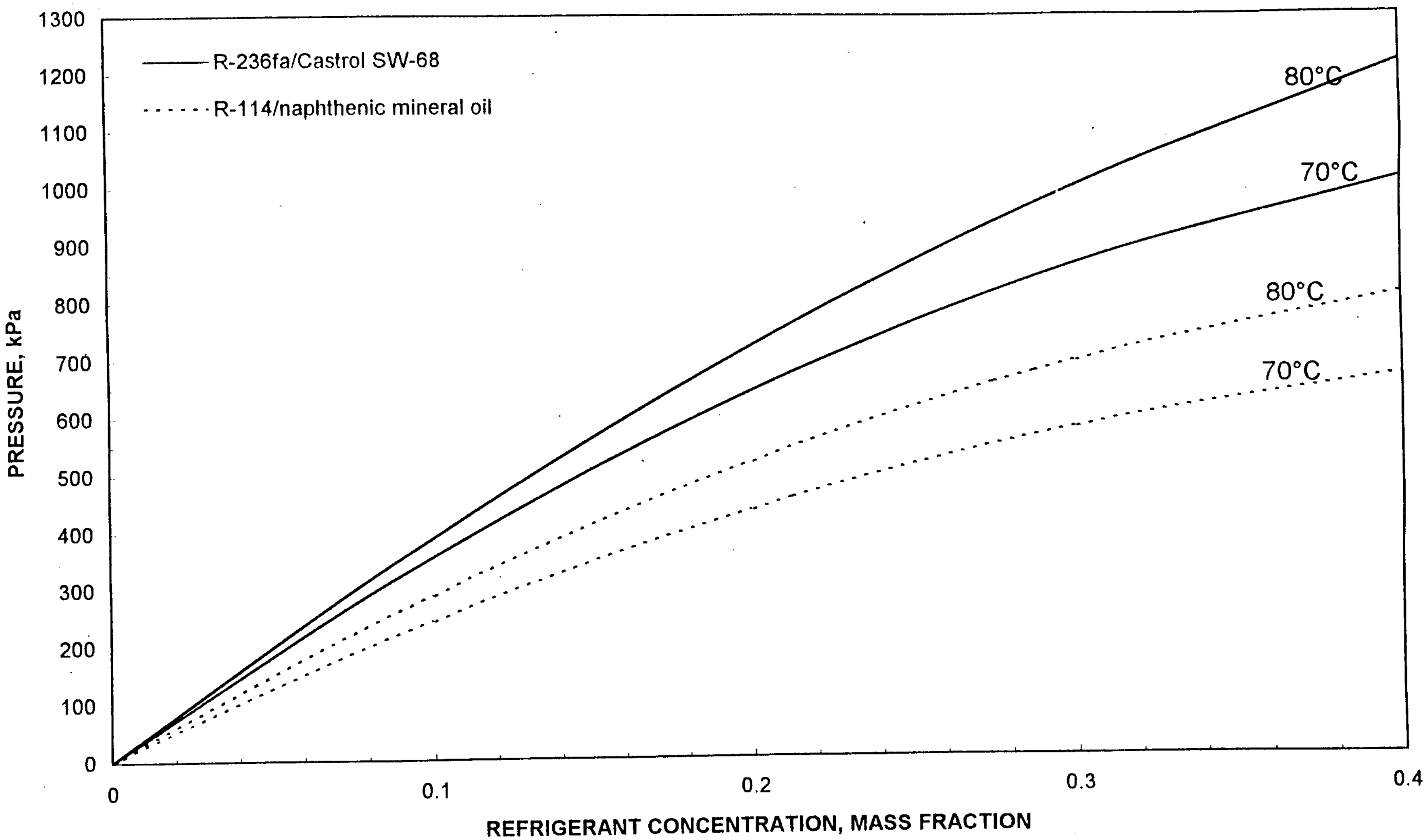

Figure 5.10. Solubility for R-236fa/Castrol SW-68 and R-114/naphthenic mineral oil at 70°C and 80°C

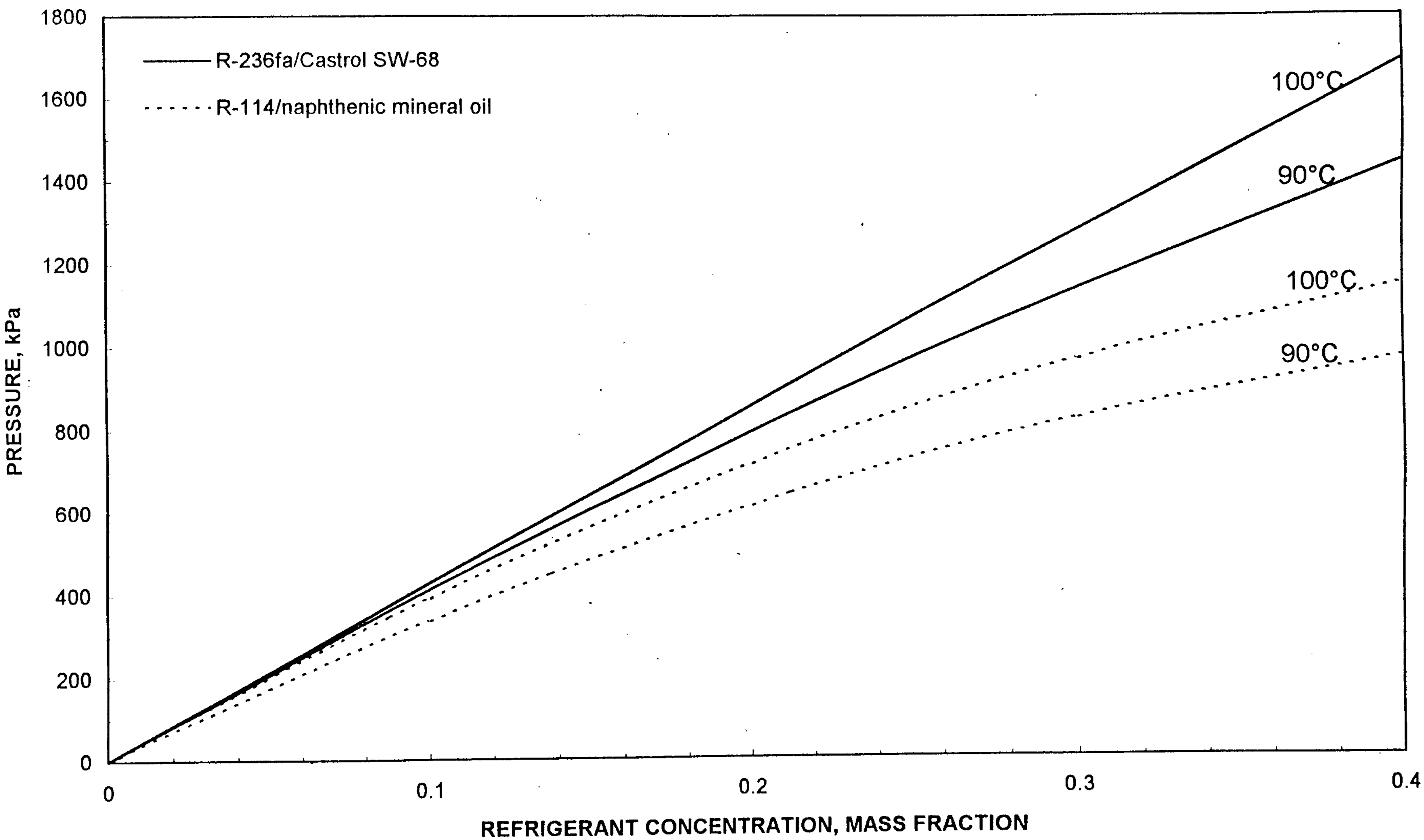

Figure 5.11. Solubility for R-236fa/Castrol SW-68 and R-114/naphthenic mineral oil at 90°C and 100°C

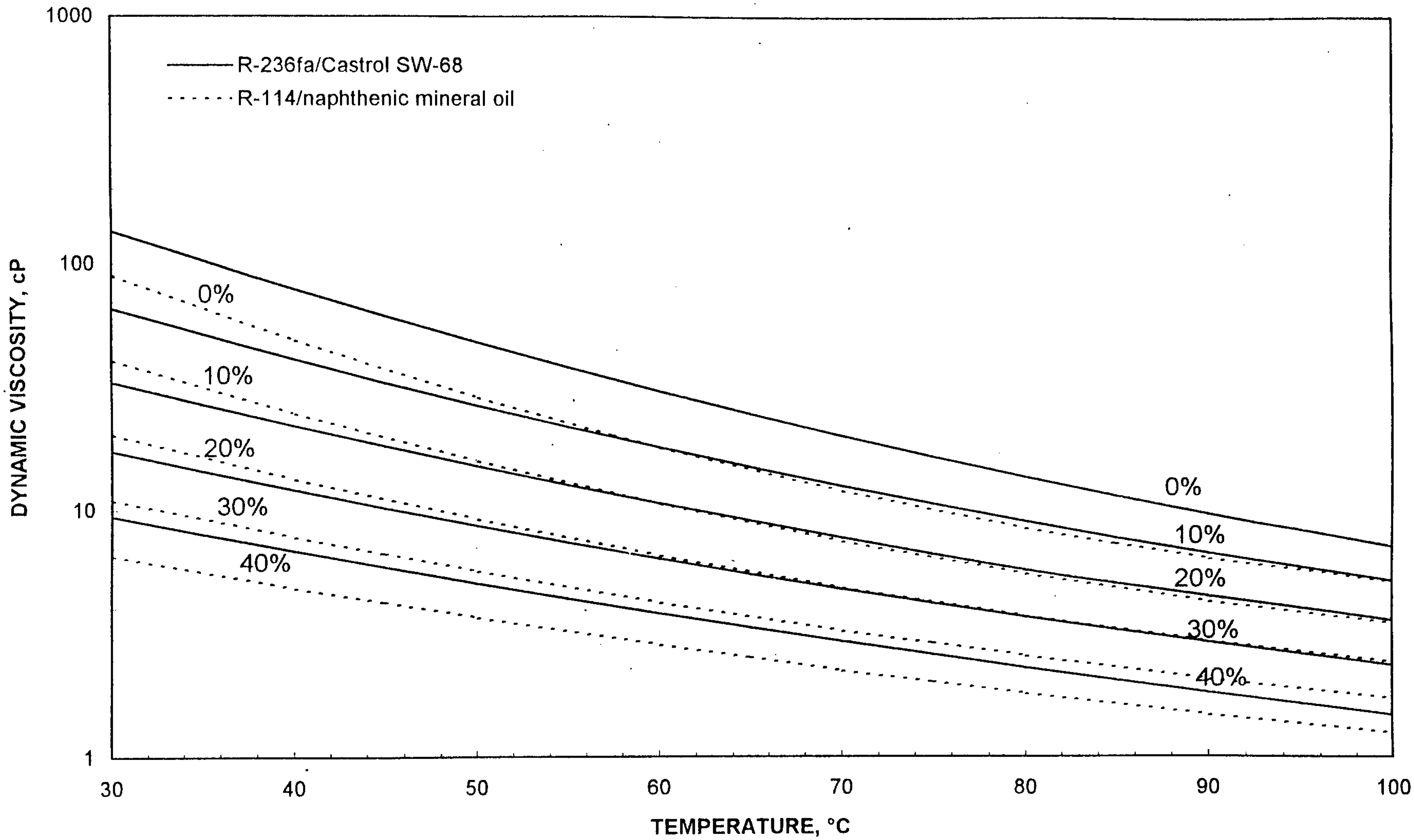

Figure 5.12. Dynamic viscosity for R-236fa/Castrol SW-68 and R-114/naphthenic mineral oil

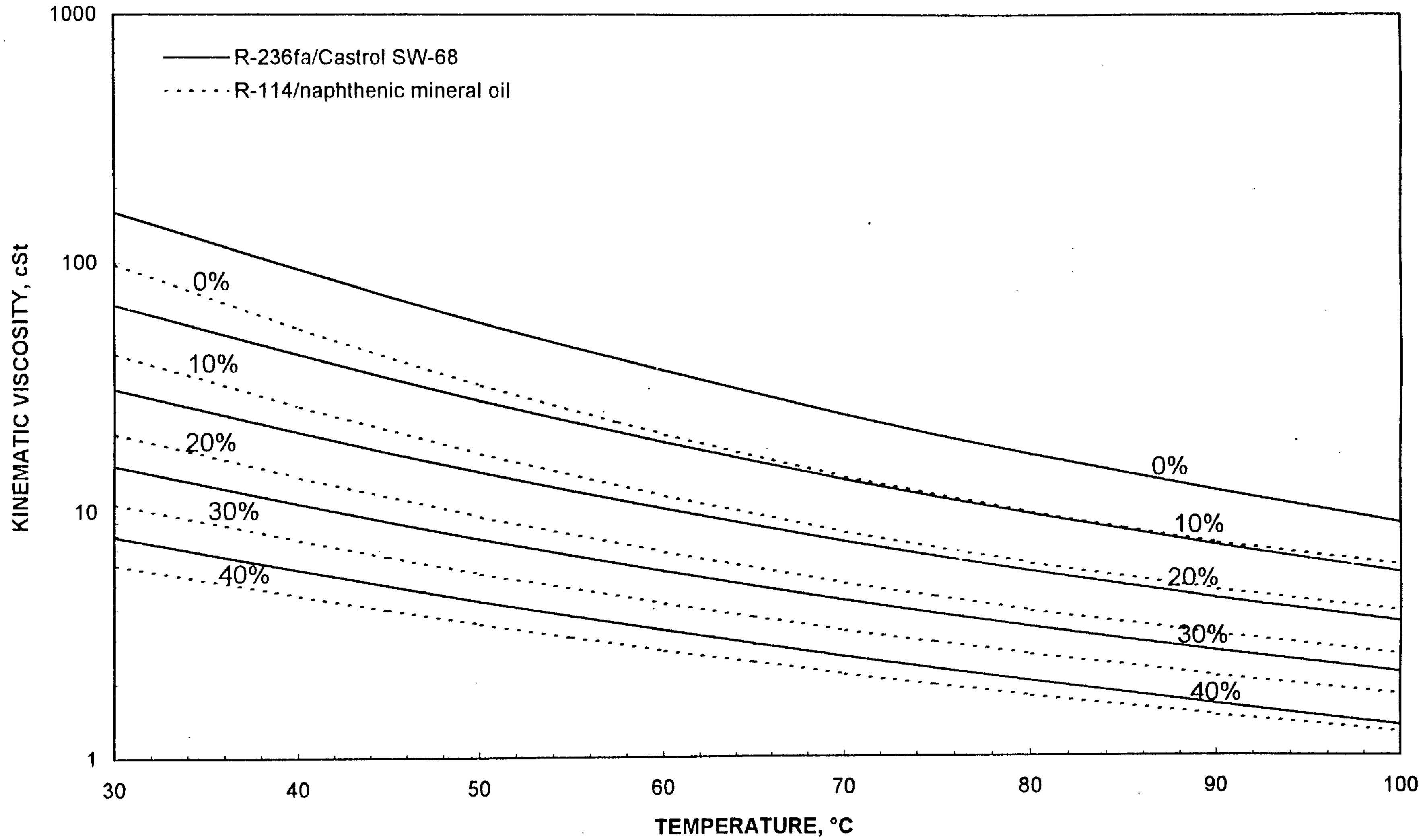

Figure 5.13. Kinematic viscosity for R-236fa/Castrol SW-68 and R-114/naphthenic mineral oil

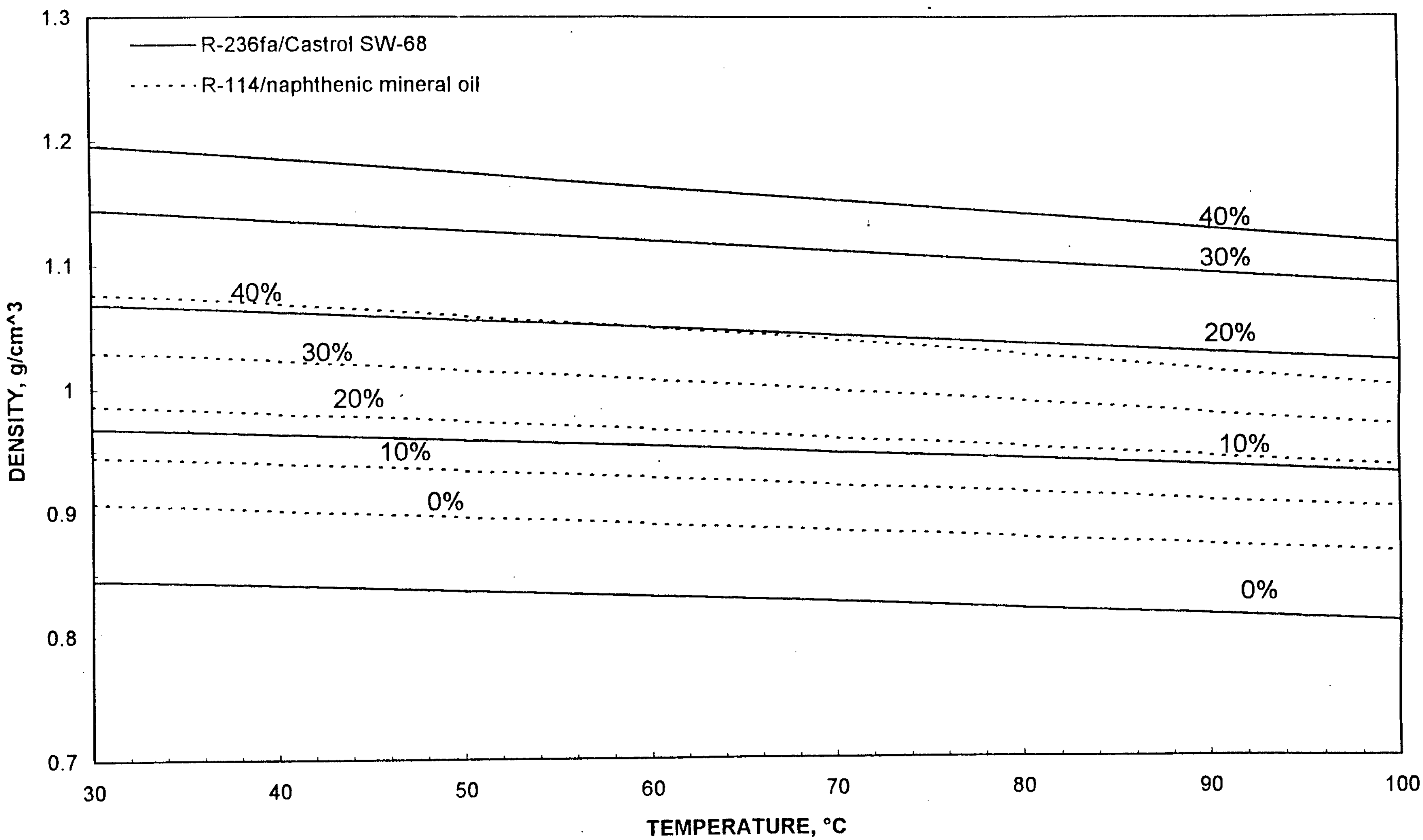

Figure 5.14. Density for R-236fa/Castrol SW-68 and R-114/naphthenic mineral oil

236ea/SW-68, and R-114/naphthenic mineral oil were all completely miscible over the temperature range tested, -40 to 90°C (-40 to 194°F).

The results of the comparisons of solubility, viscosity, and density for R-236fa/SW-68, R-236ea/SW-68 and R-114/naphthenic mineral oil at eight different temperatures and five refrigerant concentrations are presented as graphs and tables. The temperature and pressure ranges for the solubility, viscosity, and density comparisons are from 30 to 100°C (86 to 212°F) and 0 to 3.5 Mpa (0 to 500 psia), respectively.

The results of the solubility, viscosity, and density tests for R-236fa mixed with Castrol SW-68 were similar to the results for R-236ea mixed with Castrol SW-68 and R-114 mixed with naphthenic mineral oil which indicates that the mixture of R-236fa/Castrol SW-68 can be a suitable replacement for the R-114 mixed with a mineral oil.

Table 5.7. Comparison of kinematic viscosity for R-236fa/Castrol SW-68 and R-114/naphthenic mineral oil at five different refrigerant concentrations

Kinematic viscosity (cSt)										
Temp. (°C)	Refrigerant concentration (percentage by mass)									
	0 %		10 %		20 %		30 %		40 %	
	R-236fa	R-114	R-236fa	R-114	R-236fa	R-114	R-236fa	R-114	R-236fa	R-114
30	159.11	98.13	67.75	43.01	31.04	20.53	15.16	10.67	7.86	6.04
40	93.88	54.50	42.80	26.41	20.79	13.70	10.68	7.60	5.76	4.52
50	57.67	32.22	27.98	17.01	14.35	9.48	7.70	5.57	4.30	3.46
60	36.76	20.27	18.93	11.49	10.20	6.80	5.70	4.19	3.28	2.70
70	24.34	13.58	13.26	8.14	7.47	5.05	4.32	3.24	2.54	2.15
80	16.74	9.68	9.61	6.05	5.64	3.89	3.35	2.58	2.01	1.75
90	11.96	7.34	7.20	4.72	4.38	3.11	2.67	2.10	1.62	1.46
100	8.88	5.93	5.59	3.86	3.51	2.57	2.18	1.76	1.33	1.24

Table 5.8. Comparison of density for R-236fa/Castrol SW-68 and R-114/naphthenic mineral oil at five different refrigerant concentrations

Density (g/cm^3)										
Temp. (°C)	Refrigerant concentration (percentage by mass)									
	0 %		10 %		20 %		30 %		40 %	
	R-236fa	R-114	R-236fa	R-114	R-236fa	R-114	R-236fa	R-114	R-236fa	R-114
30	0.845	0.907	0.968	0.945	1.068	0.986	1.144	1.029	1.196	1.076
40	0.841	0.901	0.963	0.939	1.062	0.979	1.135	1.022	1.185	1.068
50	0.836	0.895	0.958	0.933	1.055	0.973	1.127	1.014	1.174	1.058
60	0.831	0.889	0.953	0.927	1.049	0.966	1.119	1.006	1.162	1.048
70	0.826	0.883	0.947	0.920	1.042	0.958	1.110	0.997	1.151	1.038
80	0.820	0.877	0.942	0.914	1.035	0.951	1.101	0.988	1.140	1.026
90	0.815	0.871	0.936	0.907	1.028	0.943	1.092	0.978	1.128	1.013
100	0.809	0.865	0.930	0.901	1.021	0.935	1.083	0.968	1.116	1.000

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16. ABSTRACT The report gives results of miscibility, solubility, viscosity, and density measurements for refrigerant R-236fa and two potential lubricants. (The data are needed to determine the suitability of refrigerant/lubricant combinations for use in refrigeration systems.) The tested oils were pentaerythritol ester mixed-acid (ISC68), hereafter SW-68 manufactured by Castrol, and polyol ester mixed-acid (ISC46), hereafter Arctic-46 manufactured by Mobil. Miscibility was measured in a series of miniature test cells submerged in a constant temperature bath, precisely controlled over a temperature range of -50 to 90 C. The oils tested were found to be completely miscible over the temperature and concentration ranges tested. Solubility, viscosity, and density data were also obtained for R-236fa mixed with the two oils for a refrigerant concentration of 0 to 40 wt % refrigerant over a temperature range of 30 to 100 C. This research shows that: (1) solubility, viscosity, and density are functions of temperature and concentration, (2) solubility increases with increasing temperature and refrigerant concentration (i.e., mass fraction of refrigerant), (3) viscosity decreases with increasing temperature and refrigerant concentration, and (4) density decreases with increasing temperature but increases with increasing refrigerant concentration. R-114 and naphthenic mineral oil were also tested.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS		b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Pollution	Density	Pollution Control	13B
Refrigerants		Stationary Sources	13A
Lubricants		Miscibility	11H
Solubility			07D
Viscosity			20D
Measurement			14G

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